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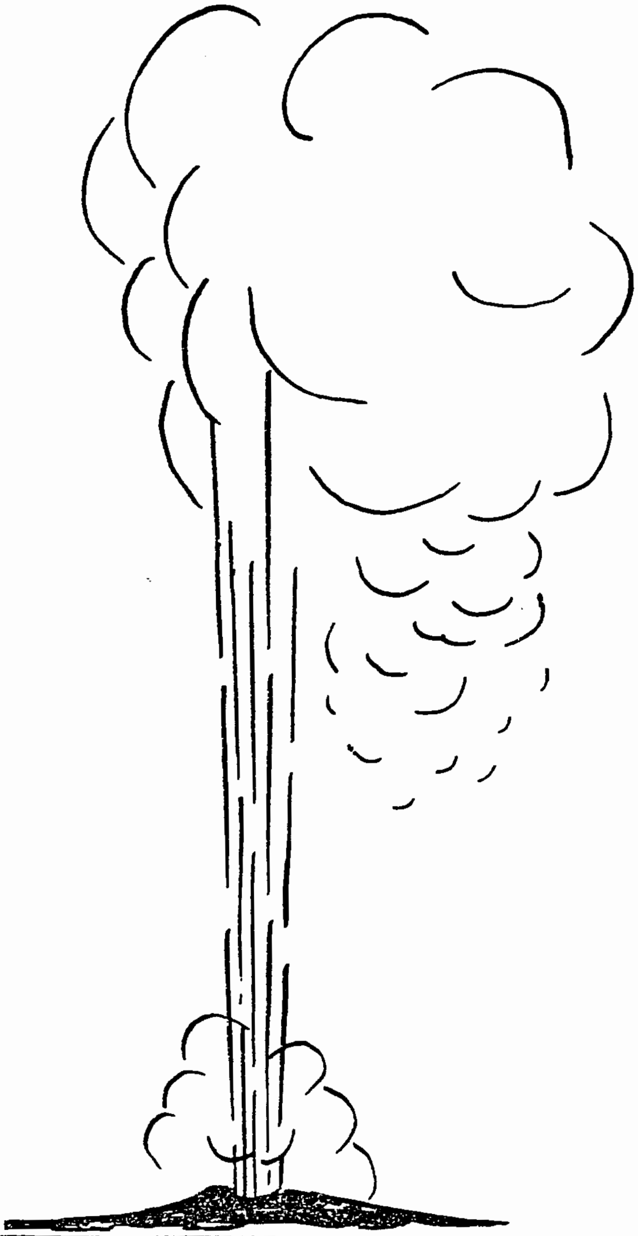

GEOTHERMAL RESOURCES OF THE EASTERN UNITED STATES

By
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Arlington, Virginia

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Executive Summary

This report on known and potential geothermal resources of the eastern United States was prepared for the Department of Energy's Division of Geothermal Energy as part of a multi-task effort under the Division's program of geothermal resource development. The resources considered are exclusively hydrothermal, and the study was confined to the 35 states east of the Rocky Mountains, excluding the Dakotas. Resource definition in these areas is based entirely on data found in the literature and in the files of a number of state geological offices.

The general geology of the eastern United States is outlined in the first section of the report. Since the presence of geothermal resources in an area is governed by the area's geology, an attempt to define useful geothermal resources is facilitated by an understanding of the geology of the area being studied. Six relatively homogeneous eastern geologic regions are discussed.

The usefulness of geothermal resources is constrained by both technological and economic factors. The accessible geothermal resource base is limited by drilling technology to the upper 10 kilometers (33,000 feet) of the earth's crust. However, only the heat in the upper 4.5 kilometers (15,000 feet) is currently considered to be useful. Geothermal waters at temperatures lower than about 40°C (104°F) are not likely to be economically exploitable except under the most favorable circumstances, and then only if found at depths of 1 kilometer (3,300 feet) or less.

Geothermal Indicators

Useful geothermal resources are normally associated with areas of above-average temperature gradient or above-average flow of heat to the earth's surface. Hence, heat flow studies are carried out in the initial phases of many geothermal exploration programs. Heat flow in the eastern United States is usually about 1×10^{-6} cal/cm^2 sec (1 heat flow unit or HFU) and temperatures change with depth at a rate of about 18.2°C/km (1°F/100 ft). The maximum values of heat flow and temperature gradient expected in this region under the most favorable conditions are about 2.3 HFU and 57°C/km (3.1°F/100 ft).

Geochemical studies are especially useful in exploring for hydrothermal energy. The silica and sodium-potassium-calcium geothermometers are the most widely recognized tools for estimating reservoir temperatures from chemical data. Regional studies of silica concentration in ground water provide important clues for identifying areas having elevated heat flow and subsurface temperature. In the eastern United States a chalcedony, rather than quartz, equilibrium is usually assumed for temperature estimates based on the silica geothermometer.

Since hydrothermal systems are often associated with tectonic activity, available subsurface temperature data in the eastern United States tend to show a good correlation with seismicity.

Indicated Geothermal Resources

The known occurrences of geothermal energy in the eastern United States fall into four categories: warm spring systems, radioactive granite plutons beneath thick sediment covers, abnormally warm aquifers, and deep sedimentary basins with normal temperature gradients.

- Warm springs with the most potential are found in the Appalachian and Ouachita Mountains and in the Trans-Pecos area of Texas. The Appalachian and Ouachita springs are associated with steeply dipping quartzite beds and also may be related to faults. Springs in the Trans-Pecos are related to Basin and Range faulting.

- Radioactive granitic plutons underlying thick, low-conductivity sediments are thought to occur beneath the Atlantic Coastal Plain and are currently the focus of a DOE-sponsored geothermal exploration program. The first deep well drilled as a part of this program encountered an aquifer with a temperature of 56°C (133°F) at 1.2 kilometers (4,000 feet) near Crisfield, Md.

- Abnormally warm aquifers, presumably caused by updip or fracture-zone movement of water, are found at several places in the Gulf Coastal Plain in Texas and Arkansas. Numerous wells at depths of 1 to 3 kilometers (3,000 to 10,000 feet) with gradients in the 30 to 40°C/km (1.6 to 2.2 °F/100 feet) range have been drilled into the Smackover Formation in southern Arkansas. Measured geothermal gradients of 25 to 45°C/km (1.4 to 2.5°F/100 feet) are reported in the Balcones and Luling-Mexia-Talco fault zones in eastern Texas. Warm waters are also thought to be present above the geopressured zones of the Gulf Coast. An extensive area of thermal waters is inferred to lie under the western third of Nebraska.

- Several deep basins exist where temperature gradients are no higher than normal but where sediments are sufficiently thick to provide elevated temperatures near basement. However, these resources cannot be utilized unless drilling costs for deep wells can be greatly reduced.

Undiscovered Resources

Undiscovered geothermal resources are most likely to exist in areas characterized by historical seismic activity or by high heat flow involving radioactive granite plutons, low-conductivity sediments, deep circulation of ground water, or combinations of these factors.

- Radioactive granite plutons are of importance only if covered by thick layers of low-conductivity sediments, and here the Atlantic Coastal Plain holds greatest promise. In general, conductivity in inland regions is too high to permit the generation of sufficiently high temperatures at reasonable depths by this mechanism.

- Deep circulation of ground water is possible under geological conditions similar to those in the folded Appalachians. Conditions in some portions of the Blue Ridge, the Piedmont, the Champlain Valley, and the Ouachita structural trend are favorable for this kind of occurrence.

Introduction

In June 1978, Gruy Federal, Inc. contracted with the Department of Energy's Division of Geothermal Energy to perform various tasks associated with the Division's program of development and utilization of hydrothermal geothermal resources in 35 eastern states. This report, prepared in fulfillment of one of these tasks, provides an overall definition of the known and potential hydrothermal geothermal resources of these states. It does not include discussion of geopressured and hot-dry-rock geothermal resources.

The report includes a brief introduction to those geological features of the eastern United States particularly important to identifying geothermal resources. The reader desiring more information should consult the references cited in the text.

All maps are on the same scale and projection as the U.S. Geological Survey Base Map of the United States (1:16,500,000), to aid in the comparison of data from map to map.

We are grateful to Chester R. Pelto, senior geologist at Gruy Federal's Arlington office, for his helpful discussions and critical review of this manuscript and to Dr. Gerald P. Brophy, DOE technical project officer, for his guidance of the project. The assistance of many state geological surveys and others interested in geothermal energy in the eastern United States is also appreciated.

General Geology of the Eastern United States

Physiographically, the eastern United States is divided into the Laurentian Upland, the Atlantic Plain, the Appalachian Highlands, the Interior Plains, and the Interior Highlands. Each major division is further divided into provinces (Fenneman, 1946), portrayed in a general way in Fig. 1. These provinces are a rough guide to the geological character of the underlying rocks. Since the correspondence is imperfect, and since geothermal resources are controlled by geological features, the following discussion is organized around areas exhibiting geologic similarity.

On the basis of geology and geothermal potential, the eastern United States is divided here into six regions, as shown in Fig. 2. This partitioning is not unique because geologic areas generally do not have sharp boundaries. The largest area considered is the Central Stable region, roughly bounded by mountain systems that lie to the west (Rockies), south (Ouachitas), and east (Appalachians). The Appalachian region includes the Northern, Central and Southern Appalachians. The Ouachita region consists of the Ouachita, Arbuckle, Wichita, and Amarillo Mountains and the deep sedimentary basins associated with them. Although the eastern coastal plain of the United States extends from Texas to Massachusetts, it is divided into the Atlantic and Gulf Coast regions because of differing geologic character and geothermal potential. A portion of West Texas--the Trans-Pecos region--is within the Basin and Range province, the bulk of which lies to the west of the Rocky Mountains. Although small, it is sufficiently different from the other regions to merit special attention.

Figure 3, a geologic map of the eastern United States, and Table 1, showing the major divisions of geologic time, are included for reference in the discussion of the six eastern regions which follows.

Central Stable Region

This region includes the oldest and most stable portion of North America. In the United States it is bordered by the Rocky Mountain system to the west, the Ouachita Mountains and related structures to the south, and the Appalachians to the east. To the north, the stable region extends into Canada.

The region can be divided into two areas: the Laurentian Shield and the Interior Lowlands. In the United States, the Laurentian Shield comprises the exposed Precambrian rocks of northern Minnesota, Wisconsin, Michigan, and the Adirondack Mountains of New York. It has been stable relative to sea level most of the time since the close of the Precambrian, and little or no sedimentary cover has been deposited over it. The Interior Lowlands are the sediment-mantled extension of the Laurentian Shield.

Little is known of Precambrian structures in the Central Stable region except where Precambrian rocks are exposed at the surface or where they act as controls for Paleozoic structures. One exception is the Mid-Continent gravity high extending from central Kansas to the Lake Superior region. Minor earthquakes have been associated with this geophysical anomaly (Steeples and others, 1979).

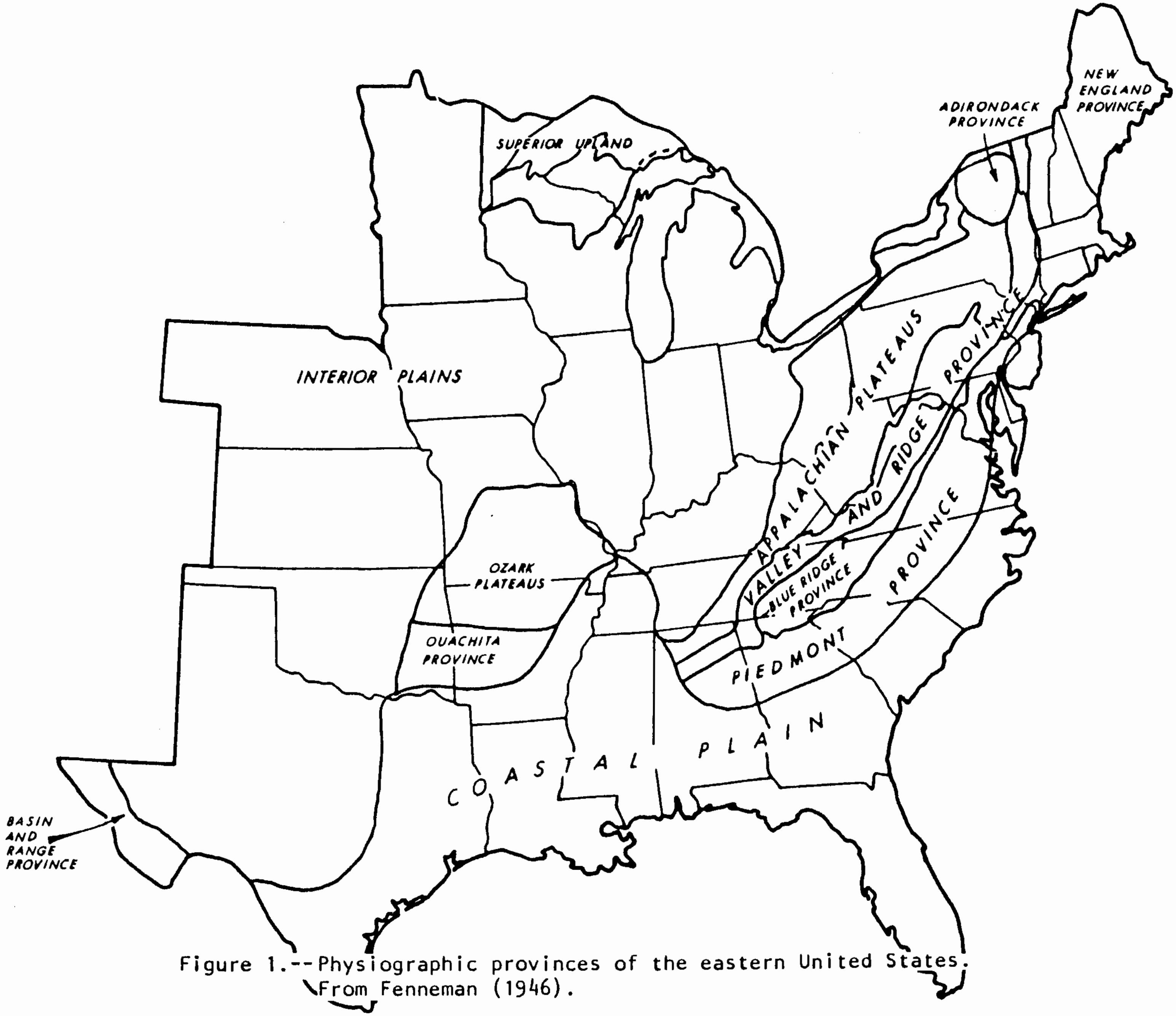


Figure 1.--Physiographic provinces of the eastern United States. From Fenneman (1946).

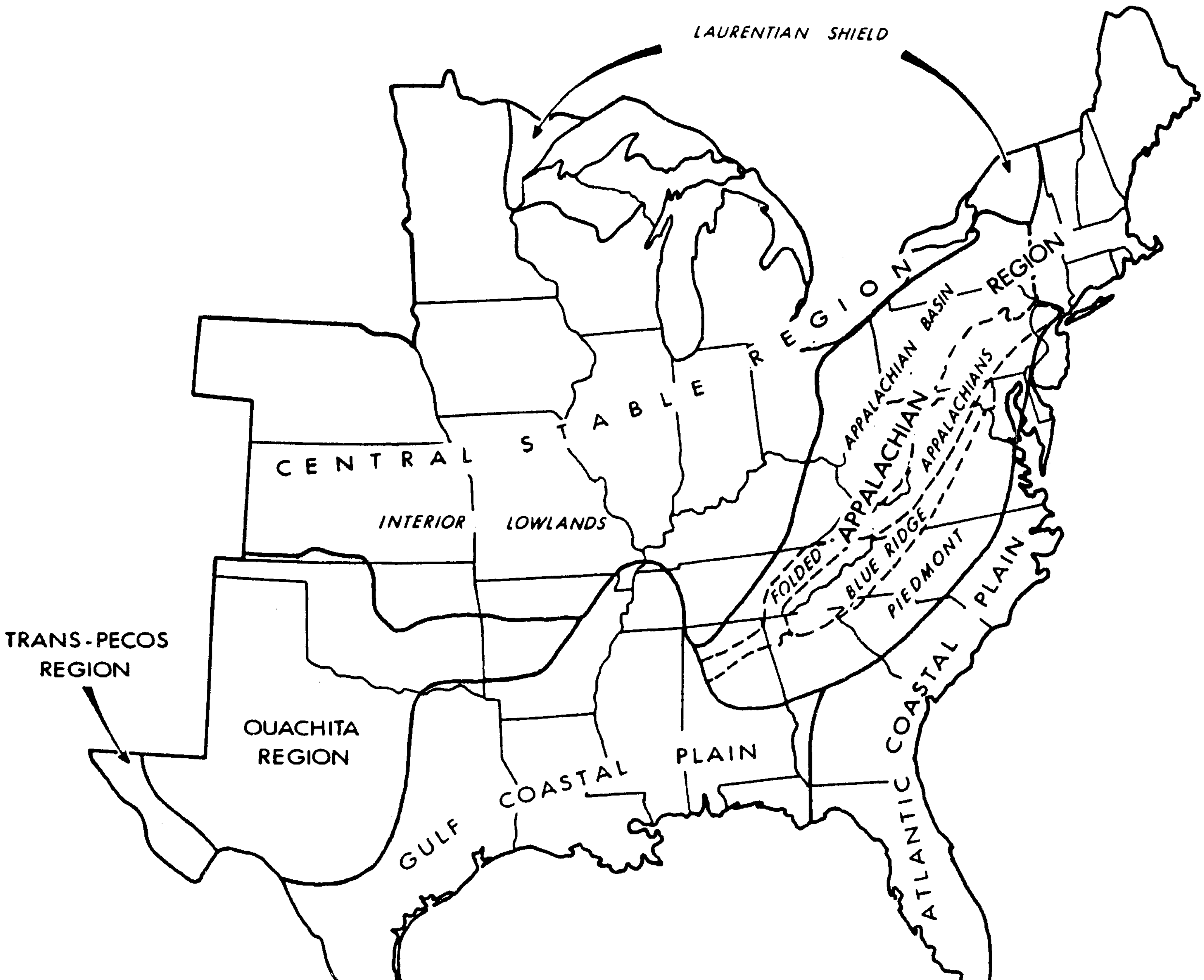


Figure 2.--Geologic regions of the eastern United States.

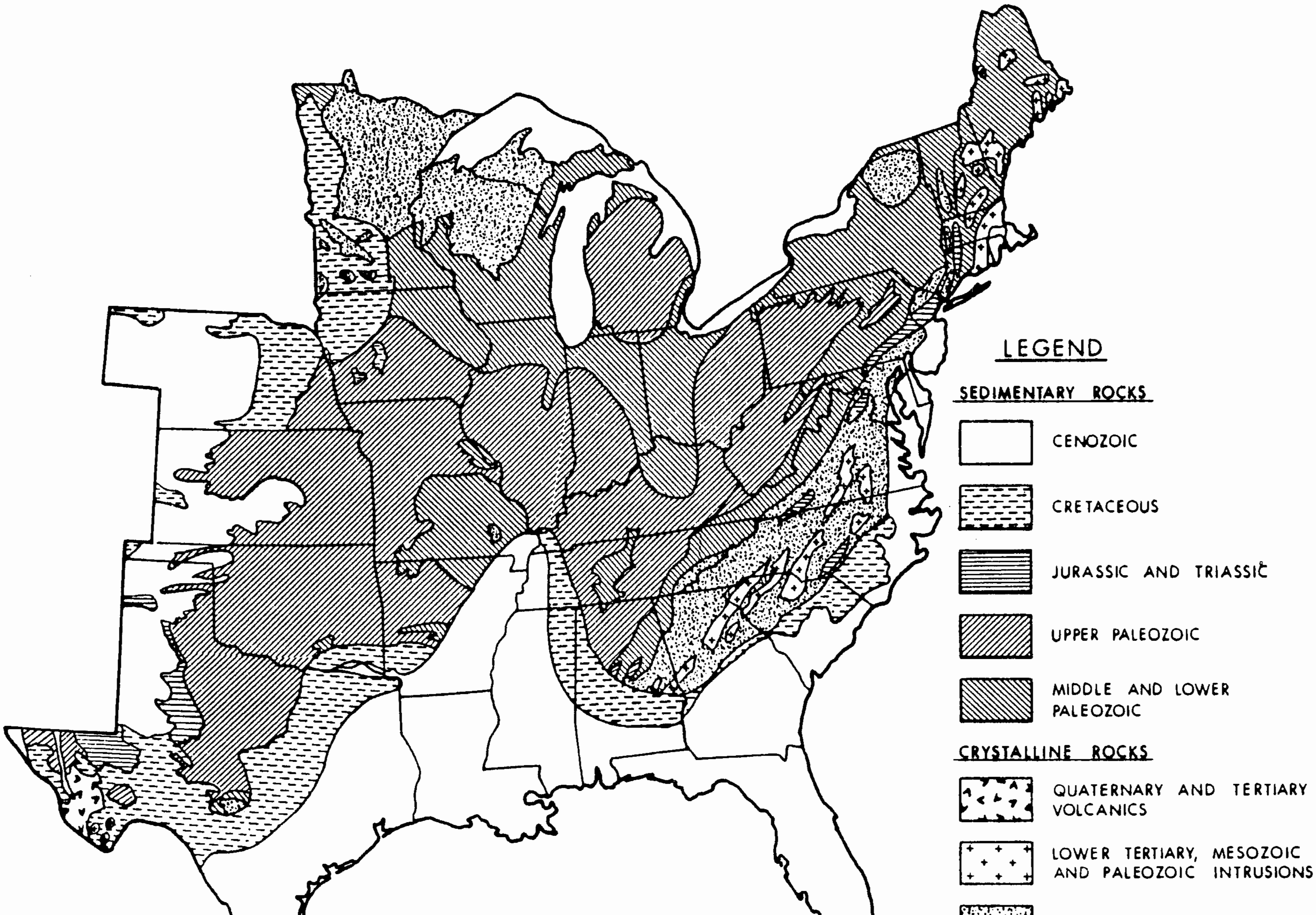


Figure 3.-- Geologic map of the eastern United States. Modified from Kinney (1966).

TABLE 1

MAJOR DIVISIONS OF GEOLOGIC TIME

ERA	PERIOD	Millions of years ago
		0
Cenozoic	Quaternary	3
	Tertiary	65
Mesozoic	Cretaceous	136
	Jurassic	195
	Triassic	225
Paleozoic	Permian	280
	Pennsylvanian	320
	Mississippian	345
	Devonian	395
	Silurian	435
	Ordovician	500
	Cambrian	570
Precambrian		

Times are based on radiogenic dating and are reported in millions of years before the present. Adapted from Newman (1978).

The major post-Precambrian structural features of the area are shown in Fig. 4. For the most part they are gentle domes or arches and shallow basins. Faulting appears not to have been important in the formation of most structures, although minor faults are associated with many of them.

Several areas of the Central Stable region were structural highs during part or all of the Paleozoic Era. Among these, the Nemaha Uplift, Central Kansas Uplift, Cambridge Arch, and Chadron Arch are associated with some recent low-level seismic activity and in some places with elevated temperature gradients. These trends may have some potential for low-temperature thermal waters. The thickness of sediments overlying crystalline rocks, or basement, is controlled by the regional slope of the Precambrian rocks away from the shield area and by the series of arches, domes, and basins developed on the basement, primarily during the Paleozoic Era. Except for the Illinois and Michigan basins and the major depositional basins associated with the Rocky, Ouachita, and Appalachian Mountain belts, sediments are not more than 1,500 meters (5,000 feet) thick within the stable region. Figure 5 is a generalized map of sediment thickness.

The Illinois and Michigan basins are typical of basins developed in stable areas. During the Paleozoic Era they accumulated up to 4,600 meters (15,000 feet) of sediments (Ells and Ives, 1964; Willman and others, 1975). The Michigan basin is the simpler of the two. Roughly symmetrical, it exhibits only minor folding and faulting. Sedimentation was almost continuous in the basin during the Paleozoic so that rocks from each period are represented in the stratigraphic column. In the structurally more complex Illinois basin the major structural element is the LaSalle anticlinal beit extending from north central to east central Illinois.

The most complexly faulted area of the central United States is an east-west trending zone along the 38th parallel from central Missouri to Virginia. The trend of faults, igneous intrusions, and mineral deposits has been termed the 38th parallel lineament by Zartman and others (1966). Heyl (1972) extends the lineament westward to the Rocky Mountains. Associated with it are the Irvine-Paint Creek, West Hickman Creek, Kentucky River, and Rough Creek fault zones in Kentucky; the Rough Creek-Shawneetown and Cottage Grove fault zones in Illinois; and the St. Lawrence and New Madrid fault zones in Illinois and Missouri.

The lineament probably overlies a major fault in the buried Precambrian rocks, and it may be the continental equivalent of such major oceanic fault trends as the Mendocino and Kelvin zones off the U.S. coasts in the Pacific and Atlantic Oceans, respectively (Heyl, 1972). Seismic activity continues along some sections of the lineament.

Appalachian Region

Basic to an appreciation of geothermal potential in the Appalachians is an understanding of their general geologic setting. Several summaries of Appalachian geology have been published in the past 11 years. The works of Rodgers (1970), Zen and others (1968), and Fisher and others (1970) are especially recommended to the reader desiring a more complete background in Appalachian geology.

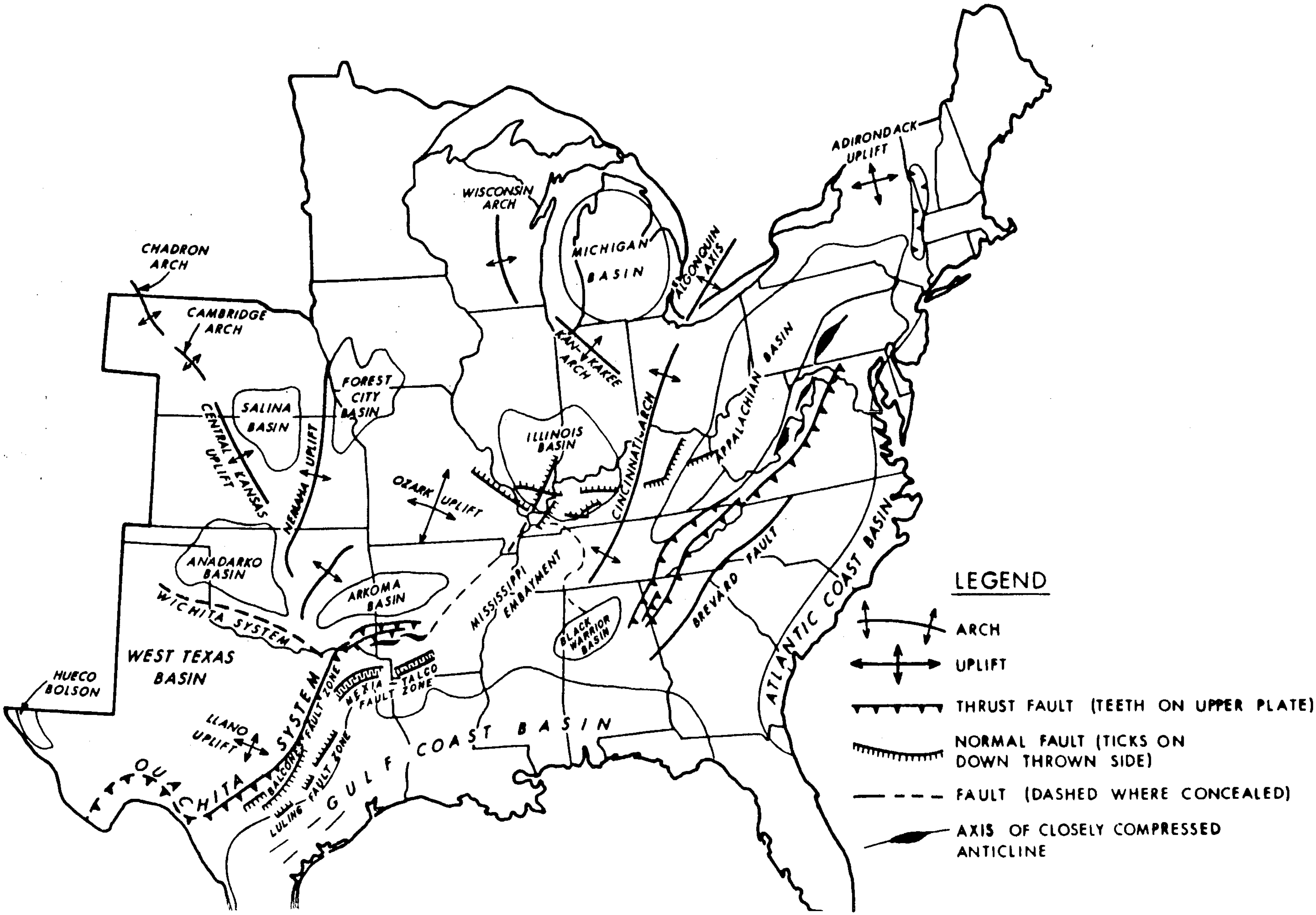


Figure 4.--Major structural features of the eastern United States. Modified from King (1969).

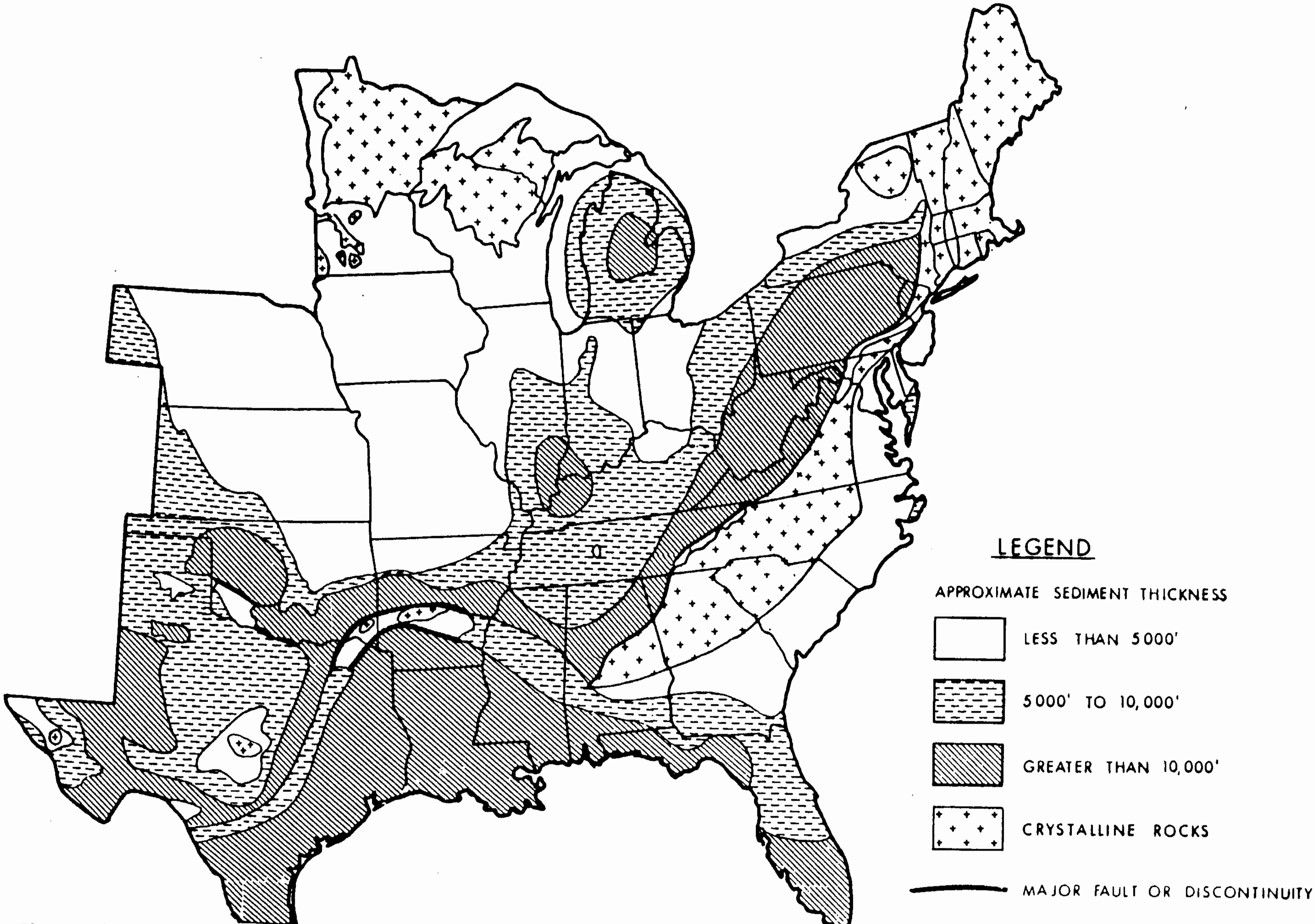


Figure 5.-- Approximate sediment thickness overlying basement. Modified from the American Association of Petroleum Geologists and United States geological Survey (1967).

Precambrian, Paleozoic, and Mesozoic tectonic activity influences the location of geothermal prospects in the Appalachian Region, rather than Cenozoic events that generally dominate geothermal manifestations worldwide. Because of the association with older tectonic features, the geothermal resources of the eastern United States are expected to be more localized and of lower grade.

In the broadest sense, the Appalachian region comprises all that part of the eastern United States where the rocks were significantly deformed during Paleozoic time. The Appalachian structural trend generally parallels the Atlantic coastline. Extending northeastward from Alabama to the Canadian Province of Newfoundland, it separates the flat-lying Paleozoic sediments of the stable Interior Lowland from the gently dipping undeformed Mesozoic and Cenozoic sediments of the Atlantic Coastal Plain. The Appalachians can be divided into three segments from southwest to northwest. The southernmost segment extends from central Alabama to near Roanoke, Va. The Central Appalachians continue from near Roanoke to New York. The third section, the Northern Appalachians, extends from New York through the New England states to the Gulf of St. Lawrence in Canada. Although all sections display many common characteristics, each has its own unique tectonic character.

The Southern and Central Appalachians are structurally divided from northwest to southeast into four provinces: Appalachian Basin, Folded Appalachians or Valley and Ridge, Blue Ridge, and Piedmont.

Appalachian Basin. In the Appalachian Basin, the strata are generally flat and maturely dissected by an arborescent drainage system. In West Virginia, Pennsylvania, and New York, the sediments are slightly deformed into a series of gentle folds, with minor folding and some faulting. The sediments have a low regional slope to the east and may attain thicknesses as great as 9 kilometers (30,000 feet) in the deepest part of the basin along Virginia's western border (King, 1969). The Appalachian Basin represents a broad transition from the flat-lying rocks, gentle arches, and domes of the stable interior to the intensely folded strata of the Folded Appalachians.

Folded Appalachians. The Paleozoic rocks in the Folded Appalachians are highly deformed to yield steep-limbed anticlines and synclines. These folded rocks produce the classic Appalachian landscape of linear ridges and valleys, commonly of great length. The physiography of the region is almost entirely controlled by the geologic structure.

The central section of the Folded Appalachians has been considered to be almost totally dominated by folding, particularly in Pennsylvania. However, some major thrust faults are present, and Gwinn (1964, p. 863) states that "the tectonic style and mode of deformation of the 'folded' Central Appalachians is . . . practically identical with that observed in the 'thrust-faulted' Southern Appalachians. The only important difference between the two regions is that the upward-shearing segments, or 'toes,' of thrust sheets in the Southern Appalachians have been exposed by erosion, whereas the toes of the major Central Appalachian thrust sheets are still covered by a mile or more of stratified rocks."

In the Southern Appalachians, folds and thrust faults dominate. Rich (1934) observed that although the area was broken by faulting, none of the faults brought the oldest rocks of the region to the surface. Sufficient information was not publicly available to document this mode of deformation until Gwinn (1964) published a summary of data from oil and gas exploration programs. That summary, together with regional seismic profiles and deep drilling reported by Jacobeen and Kanes (1974), has confirmed Rich's original concept that deformation is confined to the sedimentary rocks overlying older crystalline rocks.

This style of deformation has been called "thin-skinned" (Rodgers, 1949, p. 1653-1654). It is characterized by sheets of sediments sheared along relatively incompetent shale and thrust to the northwest. In some areas the thrust has been divided among smaller faults near the surface, causing several sheets of sediments to be thrust one upon the other. The Ray Sponaugle well in Pendleton County, W.Va., drilled to 3,963 meters (13,000 feet) in 1960, shows such a repeated section (Perry, 1964). Most of the folding visible at the surface appears to result from thrusting at depth.

Blue Ridge. The third province of the Central and Southern Appalachians, the Blue Ridge, extends from northern Georgia to southern Pennsylvania. Rocks of Blue Ridge type are exposed discontinuously farther to the northeast in the Reading Prong, the New Jersey Highlands, the Berkshire Hills, and the Green Mountains. The width of the Blue Ridge varies inversely with that of the Valley and Ridge Province. In the Central Appalachians it consists of a single mountain ridge to the southeast of the broadest section of the Valley and Ridge Province. In the vicinity of Roanoke the Blue Ridge widens at the expense of the Valley and Ridge into its southern culmination, the Great Smoky Mountains. At Roanoke, the structural style also undergoes an abrupt change comparable to the change in style of the Valley and Ridge Province at this latitude. The Blue Ridge north of Roanoke can be characterized as a fold belt which is itself arched upwards and in places overturned to the west. To the southwest, the structure is similar to that of the southern Valley and Ridge Province. Multiple thrust sheets have been mapped in the Smoky Mountains and several other areas. The warmest springs in the Appalachians issue from steeply inclined rocks of the Blue Ridge at Hot Springs, N.C.

Piedmont. The southeasternmost province of the Appalachians is the Piedmont. It slopes rather gently to the southeast from the Blue Ridge and is eventually overlain by the sediments of the Coastal Plain. The Piedmont is generally covered by a thick mantle of weathered rock that makes detailed geologic investigations difficult. The rocks are mostly Paleozoic in age, although Precambrian rocks can be recognized. Studies of exposed igneous intrusions in the Piedmont are being used in the search for geothermal resources under the Coastal Plain (Costain and others, 1976).

Several major fault zones have been mapped in the Piedmont, and structures similar to those of the southern Valley and Ridge and Blue Ridge provinces have been recognized (Hewett and Crickmay, 1937). Warm Springs, Ga., is located in one of these areas, which Rodgers (1970, p. 194) describes as resembling "the mountains in the Valley and Ridge provinces more than any in the intervening Piedmont (except Talladega Mountain in Alabama)."

The Northern Appalachians are not so easily divided into the classical Appalachian framework as the Central and Southern sections. The Appalachian Plateau setting is essentially absent north of the Catskill Mountains in New York. Valley and Ridge rock types are present in the upper Hudson and Champlain River Valley and somewhat to the east. However, the age and perhaps the style of deformation is different.

The geology of this area has been the subject of heated controversy for more than a century. Zen (1967) has proposed a generally accepted model to explain the complex structural and stratigraphic features. In its simplest form his model has the argillaceous rocks of the Taconic Mountains thrust over other Cambrian and Ordovician sediments in a manner somewhat similar to the thrusted sequences of the Southern Appalachians.

The Berkshire Hills in Connecticut and Massachusetts and the Green Mountains of Vermont are comparable to the Blue Ridge. The remainder of New England tends to correlate with the Piedmont.

Triassic basins, parallel to the trend of the Appalachians, extend from southern Vermont through North Carolina. Basins covered by younger sediments are known as far south as Alabama. They are usually found in the Piedmont Province or its northern equivalent. Two of the more prominent basins are the Newark Basin, extending discontinuously from near New York City to near Charlottesville, Va., and the Connecticut Valley Basin or graben. Sanders (1963) suggests that the Connecticut Valley contains as much as 9 kilometers (30,000 feet) of sediments. The bounding faults of the basins, where exposed in pre-Tertiary rocks, are generally silicified (Rodgers, 1970).

Several explanations for the genesis of the Triassic basins have been presented. The older theories assume rifting caused by relaxation of the forces that gave rise to the Appalachians, or rifting caused by rebound of a thickened crust after the final episodes of Appalachian mountain building. More recently the basins have been studied in the light of continental drift theory and are viewed as a major continental rift system comparable to the modern East African rift system.

Ouachita Region

The region comprises two principal belts of deformation, the Wichita and the Ouachita systems (Fig. 4) and the deep sedimentary basins associated with them. The Wichita system, extending westward from the Ouachita Mountains, is exposed in the Wichita and Arbuckle Mountains of Oklahoma and in the Amarillo Mountains of the Texas Panhandle. Although the rocks of the Wichita trend have been intensely deformed, particularly in the Arbuckle Mountains, they lack the long parallel thrusts and folds of the Appalachian Valley and Ridge. Deformation of the Wichita belt preceded the Ouachita deformation.

The Ouachita structural belt is a Paleozoic feature that rims the Gulf Coastal Plain, extending from Mexico to the Marathon region of west Texas up through Waco and across southern Oklahoma, Arkansas, and Mississippi (Fig. 4). Some geologists believe the belt may stretch into central Alabama and even as far east as northern Florida (Flawn, 1959). Others think it may be an extension of the southern Appalachians, since both the Valley and Ridge and the Ouachita Tectonic Belt were deformed during Pennsylvanian time (Thomas, 1977; King, 1969).

There are only three exposures of the Ouachita system in the United States: in the Solitario and Marathon Uplifts and in the Ouachita Mountains. The major exposure is in the Ouachita Mountains, which are characterized by east-west trending, folded and faulted Paleozic strata quite similar to the structures of the Folded Appalachians. To the south and east, the Ouachita system is covered by the Cretaceous and younger sediments of the Gulf Coastal Plain.

The West Texas Basin lies between the Wichita and Ouachita systems. To the north of the Wichita and Ouachita Mountains lie the Arkoma, Ardmore, and Anadarko basins.

The Arkoma Basin is a northeast-southwest trending basin bounded on the north by the Ozark Uplift and on the south by the Ouachita Mountains. The thickness of the sedimentary section ranges from 1 kilometer (3,300 feet) on the northern edge to 10 kilometers (30,000 feet) near the Ouachita Mountains. Block faulting, folds, and northward overthrust beds are common structural features.

The Ardmore Basin is a small, deep basin bounded on the north by the Arbuckle Mountains uplift, on the southeast by the Ouachita belt, and on the southwest by the Wichita Mountains. Sediment thickness exceeds 6 kilometers (20,000 feet).

The Anadarko Basin in central Oklahoma trends northwest-southeast. Thickness of sediments in the basin ranges from 1.3 kilometers (4,300 feet) on the edge to 12.3 kilometers (37,000 feet) in the deepest part.

Gulf Coastal Plain

Within the United States, the Gulf Coastal Plain stretches from the southern tip of Texas along the Gulf Coast into Florida. It generally extends inland from 240 to 490 kilometers (150 to 300 miles) and up to 960 kilometers (600 miles) in the Mississippi Embayment. Mesozoic and Cenozoic sediments form a thick wedge of gulfward-sloping sediments. The Mesozoic rocks are generally fine-grained marine deposits. Tertiary strata consist primarily of more coarse-grained, land-derived sediments. The lowermost strata are red beds and evaporites, probably of Jurassic age. Thick deposits of rock salt underlie Mississippi, Arkansas, Louisiana, and Texas.

The Balcones Fault Zone (Fig. 4) is a series of en echelon normal faults extending from the Del Rio area in southwest Texas around the southeast side of the Llano Uplift and north to Waco. The faults, which are downthrown on the southeast, are developed in Cretaceous strata and roughly follow the trend of the buried Ouachita system.

The Luling-Mexia-Talco Fault System, to the east and northeast of the Balcones, parallels the Balcones Fault Zone and then curves to the northeast. The Luling-Mexia-Talco faults are downthrown on the northwest. Major movement may have occurred during the Oligocene (Eardley, 1951). The downthrown areas between the Balcones and Luling-Mexia-Talco Fault zones form grabens.

Atlantic Coastal Plain

The Atlantic Coastal Plain extends eastward from the Piedmont province along the Atlantic coastline from Long Island to Georgia and northeastern Florida. (Southwestern Georgia and the Florida Panhandle are included in the Gulf Coastal Plain.) It is generally considered to be a southeastward continuation of the Piedmont. The Florida peninsula is a separate section of the Coastal Plain, included here with the Atlantic Coastal Plain for simplicity.

Only limited information is available concerning the crystalline rocks underlying the Coastal Plain. The sediments of the Coastal Plain are Mesozoic and Cenozoic sandy and clayey rocks. The basement surface and the sediments slope gently toward the ocean, with the sedimentary wedge thickening toward the sea, reaching a maximum thickness of about 3 kilometers (10,000 feet) in the vicinity of Cape Hatteras, N.C. (Brown and others, 1972).

Two models for the coastal plain sediments are currently applied. The older model assumes sedimentary beds gently sloping and thickening seaward with little or no deformation and faulting. A newer model proposed by Brown and others (1972) envisions the Coastal Plain sediments deposited on older rocks consisting of a mosaic of crustal blocks, with the geometry and relative position of each crustal block controlling the depositional environment of the overlying sediments. If the new model is correct, aquifer systems probably would be more variable and localized than in the traditionally accepted "layer-cake" model.

Trans-Pecos Region

The Trans-Pecos region (Fig. 2) of west Texas is part of the Basin and Range physiographic province. It is bounded on the south by the Mexican fold belt, on the northeast by the West Texas Basin, and on the west by the Chihauhua tectonic belt (Henry, 1979). The region is characterized by north- and northwest-trending, block-faulted mountains surrounding flat desert basins or bolsons. Movement of the normal faults in the region is thought to be continuing (Henry, 1979).

The sediments supplied by the erosion of the nearby mountains filled the bolsons during the Miocene. The Hueco Bolson (Fig. 4), east of El Paso, has as much as 2,750 meters (9,000 feet) of sediments. The sediments of the Presidio Bolson and the Labo Valley probably do not exceed 910 to 1,400 meters (3,000 to 4,500 feet) in thickness. The Salt Basin, east of the Diablo Plateau, is relatively shallow; its maximum sediment thickness is 750 meters (2,500 feet). The Rio Grande Trough, extending from south central New Mexico into west Texas near El Paso has about 300 meters (980 feet) of sedimentary fill.

The Rio Grande Rift Zone may extend into the Trans-Pecos region. The Hueco and Mesilla Bolsons near El Paso are considered to be a part of this zone (Henry, 1979).

Geothermal Resources

The most obvious manifestations of the earth's thermal energy are in areas of recent volcanism and tectonic activity. It is only natural that the search for and the utilization of geothermal energy has been concentrated in these areas of readily visible high-temperature sources possibly suitable for generation of electricity. Recently, however, attention has shifted to moderate- (90-150°C, 194-302°F) and low-temperature (less than 90°C, 194°F) resources for possible direct-use applications. Consequently, definition of the geothermal potential of the geologically stable and heavily populated eastern half of the United States has begun to receive increasing emphasis.

Resource Terminology

Geothermal energy is a relatively new energy resource for which the scientific terminology is still being developed. Similar terms have often been used with differing intent by different authors. However, any internally consistent set of resource terms developed for geothermal energy should also fit into the framework developed for mineral resources. Muffler and Cataldi (1978) present such a unified terminology for geothermal resource assessment. Their definitions, which will be used in this report, are given below, and Fig. 6 is a diagram showing the relationships among the terms.

> Geothermal resource base in a specified area is all the heat in that portion of the earth's crust existing at temperatures higher than the local mean ambient surface temperature.
>
> Accessible resource base is that part of the resource base accessible by drilling.
>
> Useful resource base represents heat that could reasonably be extracted at costs competitive with other energy sources, now or at some specified future time under improved economics or technology.
>
> > Economic resource is the heat that can be legally and economically extracted under today's conditions.
> >
> > Subeconomic resource is the heat which is not currently cost-competitive or legally extractable, but which would be at a specified future time under improved economics or different legal status.
>
> Residual resource base represents accessible heat that cannot be collected and utilized under even the most optimistic conditions.
>
> Inaccessible resource base is the heat energy in the crust that cannot foreseeably be reached with projected drilling capability.

The above discussion divides the resource base into an economic/technologic hierarchy. To complete the descriptive classification of geothermal ener-

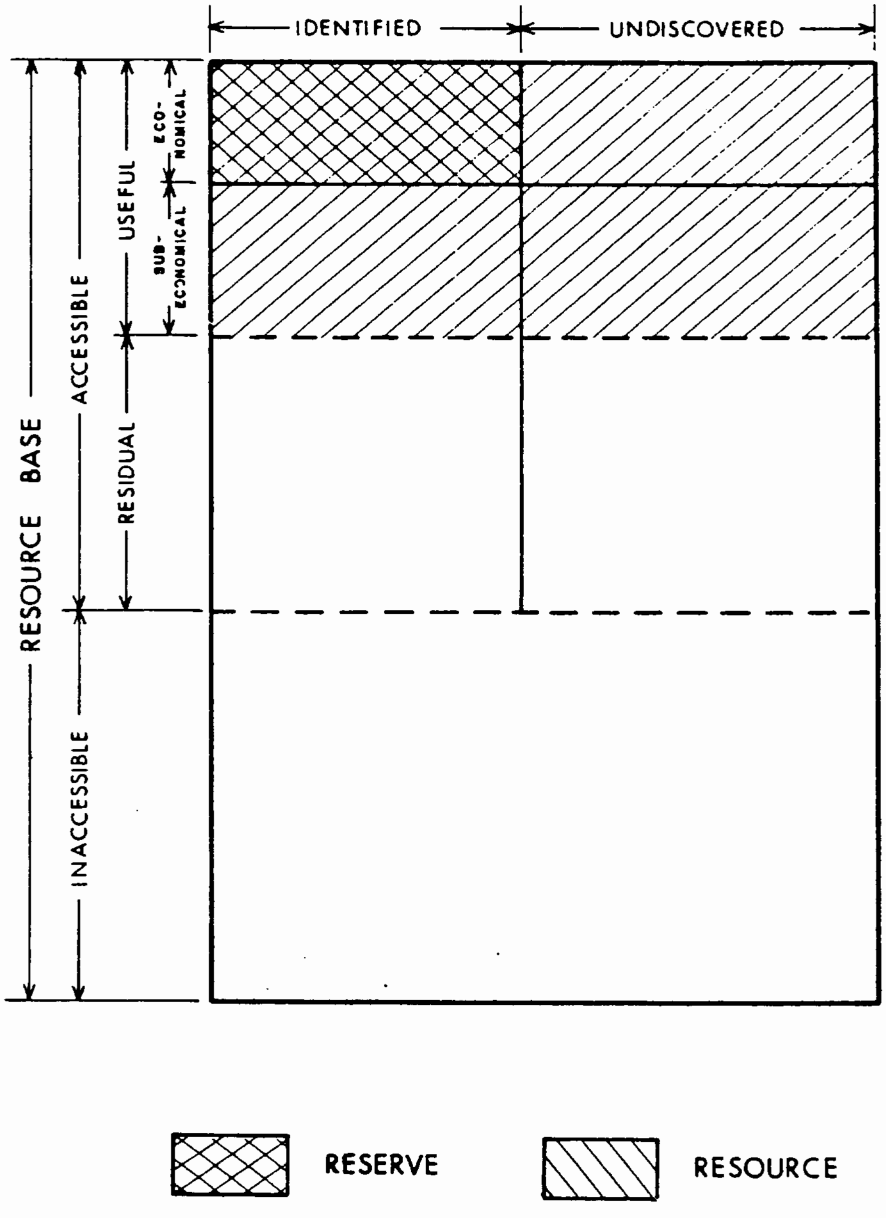


Figure 6.--"McKelvey" diagram showing the derivation of geothermal resource terminology by Muffler and Cataldi (1978).

gy, the degree of geologic assurance should also be specified. The result is the "McKelvey diagram" (McKelvey, 1972) for geothermal resources shown in Fig. 6.

The term "identified" refers to specific concentrations of heat known to exist either from drilling and testing or from geologic, geochemical, or geophysical evidence. The term "undiscovered" refers to unspecified concentrations of heat thought to exist on the basis of broad geologic knowledge.

Our experience with geothermal energy is so meager that the physical limits of the various resource classes are known only in the vaguest way. However, provisional limits for depth and temperature can be set. The accessible resource base can be assumed to lie in the upper 10 kilometers (30,000 feet) of the earth's crust--the approximate maximum depth attainable by drilling technology. It seems probable at this time that the accessible resource base below about 4.5 kilometers (15,000 feet) should not be considered useful resources. (Wells deeper than 3 kilometers (10,000 feet) are uncommon in geothermal exploration, even in areas of high-temperature resources).

Geothermal waters at temperatures below 40°C (104°F) are not likely to be used directly even under the most favorable circumstances. Public acceptance of groundwater heat-pump technology utilizing thermal waters could lower the useful temperature limit to about 13°C (55°F), a value approximating the average groundwater temperature in much of the United States.

Sammel (1979, p. 87) states that "under current or near-future economic conditions, low-temperature waters more than 1 kilometer deep are probably not attractive targets for exploration or development at most places except where usable deep wells have already been drilled for other purposes." Low-temperature waters are those at temperatures less than 90°C (194°F) but greater than 10°C (18°F) above mean annual air temperatures (Sammel, 1979). We are reluctant to estimate a maximum depth below which waters at about 40°C should not be considered as resources, but we provisionally accept 1 kilometer (3,300 feet) as an approximate limit. Our discussion of geothermal potential in the eastern United States places most emphasis on areas where the subsurface increase in temperature is at least 29°C/km (1.6°F/100 ft) and areas with warm springs at temperatures 10°C (18°F) or more above average ambient surface temperature.

Indicators of Geothermal Resources

Geothermal resources are found where nature has provided abnormal concentrations of heat near enough to the surface to be exploited. Until the past few years, geothermal exploration has been guided by surface manifestations of elevated temperature--warm springs, geysers, and recently active volcanoes. As the search for geothermal resources has expanded, more sophisticated methods and combinations have been used, so that the geologic setting of geothermal resources has been delineated to some degree, and regional assessments have been prepared (White and Williams, 1975; Muffler, 1979).

The greatest potential for geothermal energy exists in areas of above-average heat flow; that is, areas of recent volcanic activity or active tectonics. Because the eastern United States is tectonically stable and has experienced no volcanic activity recent enough to provide heat from crystallization, the search for geothermal resources in the east must consider other means of heat generation and accumulation.

Three likely sources of elevated subsurface temperatures in the eastern United States are:

1. Granitic plutons (igneous intrusions) enriched in uranium and thorium that produce elevated heat flow as the result of radioactive decay.

2. Thick sediments of low heat conductivity that cause above-average thermal gradients by allowing the accumulation of heat below them. Costain and others (1977, 1978, 1979) have used this and the preceding concept to model potential geothermal sites in the Atlantic Coastal Plain.

3. Movement of deep waters upward along rock layers or through faults and fractures to produce accumulations of warm water in reservoirs relatively near the surface or warm springs at the surface.

Temperature gradients, heat flow, geochemistry, seismic activity, and regional geology yield the principal clues to such thermal accumulations.

Temperature gradients and heat flow. The temperature gradient (Γ) and heat flow (q) are related to the conductivity (K) of the rocks through which the heat is passing by the relation $q = K\Gamma$. Geophysicists have traditionally recorded q in heat flow units (1 HFU $= 1 \times 10^{-6}$ cal/cm^{2}sec), with K in conductivity units (1 CU $= 1 \times 10^{-3}$ cal/cm sec °C) and temperature gradient in °C/km.

Early heat flow studies in the United States showed that the continent could be divided into several provinces typified by characteristic heat flows (Roy and others, 1968a,b), and that the variation of heat flow within a province is caused by differences in the heat generated in upper crustal rocks (Birch and others, 1968). Birch and coworkers found a linear relationship between heat flow and radioactive heat generation (A) in the rocks at each site: $q = q^* + DA$. Here, q^*, reduced heat flow, is the heat flow characteristic of a given province, DA is the component of heat flow due to radioactive heat generation in the upper crust, and D, which changes from one region to another, is related to the thickness of the radioactive crust. Diment and others (1975) suggest values of 0.8 HFU and 7.5 kilometers for q^* and D, respectively, in the eastern United States. Costain and others (1979) use $q^* = 0.65$ HFU and $D = 8.1$ kilometers in the Piedmont province.

As further studies are made, more detailed heat flow and reduced heat flow (q^*) data will be available in addition to those provided by Sass and others (1976). The data used by Sass and others, together with more recent data are listed in Table 2 and shown in Fig. 7. The figure and table show

TABLE 2

HEAT FLOW VALUES IN THE EASTERN UNITED STATES

	State	Location Lat.(N)	Long.(W)	Heat Flow ($cal/cm^2 sec$)	Reference
1	Alabama	34°44'	86°30'	0.41	(4)
2		34°44'	86°30'	0.44	(4)
3		33°56'	84°50'	0.24	(4)
4		33°16'	86°01'	0.95	(1)
5		33°18'	87°16'	1.11	(4)
6		31°00'	88°15'	0.95	(4)
1	District of Columbia	39°00'	77°00'	1.12	(1)
1	Florida	30°47'	82°01'	0.5	(5)
2		30°35'	87°07'	1.3	(5)
3		location uncertain		0.9	(5)
4		29°42'	82°53'	0.1	(5)
5		29°38'	81°38'	0.8	(5)
6		28°28'	81°13'	0.92	(1)
7		28°04'	82°47'	0.7	(5)
8		location uncertain		0.9	(5)
9		27°22'	82°16'	1.2	(5)
10		27°21'	82°33'	0.8	(5)
11		location uncertain		0.7	(5)
1	Georgia	34°32'	84°52'	0.34	(3)
2		34°25'	84°21	1.0	(3)
3		34°05'	83°46'	0.64	(3)
4		33°	85°	1.0	(1)
5		33°30'	84°42'	0.94	(2)
6		33°29'	83°12'	1.58	(2)
7		33°27'	83°09'	1.53	(2)
8		33°13'	84°15'	0.97	(1)
9		32°43'	83°15'	0.92	(3)
10		31°36'	81°36°	1.24	(3)
11		31°08'	81°30'	0.51	(3)
1	Illinois	41°01'	88°54'	1.41	(1)
2		40°49'	87°54'	1.42	(1)
3		40°46'	87°48°	1.39	(1)
4		40°45'	87°47'	1.44	(1)
1	Indiana	41°23'	86°14'	1.28	(1)
2		40°59'	84°52'	0.97	(1)
3		40°55'	86°28'	1.41	(1)
4		40°55'	86°27'	1.39	(1)
5		40°53'	86°28'	1.40	(1)

TABLE 2 (cont.)

HEAT FLOW VALUES IN THE EASTERN UNITED STATES

	State	Location Lat.(N)	Long.(W)	Heat Flow (cal/cm^2sec)	Reference
1	Kansas	37°57'	101°45'	1.55	(1)
2		38°23'	98°10'	1.50	(1)
1	Maine	44°24'	68°37'	1.44	(1)
2		44°03'	70°37'	1.80	(1)
1	Maryland	38°26'	75°04'	1.45	(2)
2		38°24'	76°11'	1.3	(2)
3		38°24'	75°34'	1.2	(2)
4		38°21'	75°36'	1.5	(2)
5		38°01'	75°50'	1.6	(2)
1	Massachusetts	42°38'	71°25'	1.63	(1)
2		42°37'	72°27'	1.67	(1)
3		42°23'	71°07'	1.20	(1)
4		41°45'	70°05'	1.16	(1)
1	Michigan	47°49'	88°54'	0.75	(1)
2		47°35'	88°13'	0.79	(1)
3		47°24'	88°01'	0.99	(1)
4		47°17'	88°28'	0.93	(1)
5		47°11'	91°15'	0.30	(1)
6		46°45'	89°34'	1.05	(1)
7		44°12'	85°11'	1.10	(1)
8		44°09'	85°00'	1.20	(1)
9		44°04'	85°05'	1.30	(1)
10		44°03'	85°05'	1.10	(1)
11		43°50'	85°35'	1.20	(1)
12		43°32'	85°16'	1.20	(1)
13		43°32'	85°36'	1.00	(1)
14		42°48'	82°44'	0.80	(1)
15		42°44'	86°00'	0.90	(1)
16		42°43'	85°49'	1.07	(1)
17		42°26'	83°34'	1.39	(1)
18		42°26'	83°34'	1.20	(1)
19		42°06'	83°23'	0.8	(1)
1	Minnesota	47°49'	91°43'	0.82	(1)
2		47°09'	95°12'	0.89	(1)
3		46°06'	93°42'	1.03	(1)
4		44°54'	93°12'	1.15	(1)
1	Missouri	39°05'	94°10'	1.17	(1)
2		38°09'	91°15'	1.24	(1)

TABLE 2 (cont.)

HEAT FLOW VALUES IN THE EASTERN UNITED STATES

	State	Location Lat.(N)	Long.(W)	Heat Flow (cal/cm^2sec)	Reference
3	Missouri	37°39'	91°10'	1.2	(1)
4		37°30'	90°40'	1.24	(1)
1	New Hampshire	44°06'	72°00'	1.34	(1)
2		44°04'	71°10'	1.89	(1)
3		44°02'	71°29'	2.27	(1)
4		43°56'	71°32'	2.15	(1)
5		43°16'	71°59'	1.59	(1)
6		43°12'	71°32'	1.73	(1)
7		43°07'	70°55'	1.08	(1)
8		42°47'	72°08'	1.63	(1)
1	New Jersey	41°06'	74°35'	0.91	(1)
2		39°50'	74°11'	1.05	(2)
1	New York	44°35'	73°54'	1.22	(1)
2		44°20'	74°16'	0.81	(1)
3		44°16'	75°25'	1.22	(1)
4		44°14'	73°28'	0.79	(1)
5		44°13'	73°32'	0.81	(1)
6		43°18'	73°37'	1.05	(1)
7		43°12'	78°28'	1.18	(1)
8		43°05'	79°00'	1.16	(1)
9		42°48'	78°51'	1.20	(1)
10		42°34'	76°57'	1.55	(1)
11		42°27'	78°38'	1.19	(1)
12		42°27'	74°26'	1.00	(1)
13		42°25'	76°54'	1.72	(1)
1	North Carolina	36°26'	78°54'	0.88	(2)
2		36°26'	79°02'	0.97	(2)
3		36°23'	78°58'	0.98	(2)
4		36°20'	78°50'	0.94	(2)
5		36°01'	80°25'	1.44	(2)
6		36°04'	78°08'	0.31	(3)
7		35°55'	82°07'	1.05	(2)
8		35°57'	78°20'	1.02	(2)
9		35°47'	78°25'	1.30	(2)
10		35°45'	75°48'	1.90	(2)
11		35°44'	78°20'	1.13	(2)
12		35°41'	78°56'	0.64	(4)
13		35°40'	75°45'	1.64	(4)
14		35°38'	82°10'	0.84	(4)
15		35°26'	83°27'	1.05	(4)
16		35°17'	80°53'	0.33	(4)

TABLE 2 (cont.)

HEAT FLOW VALUES IN THE EASTERN UNITED STATES

	State	Location Lat.(N)	Location Long.(W)	Heat Flow ($cal/cm^2 sec$)	Reference
17	North Carolina	34°07'	78°20'	1.64	(4)
1	Oklahoma	36°59'	94°52'	1.4	(1)
1	Pennsylvania	41°56'	77°51'	1.47	(1)
2		41°52'	78°00'	1.31	(1)
3		41°12'	78°39'	1.31	(1)
4		40°59'	80°08'	1.2	(1)
5		40°34'	75°12'	0.89	(1)
6		40°22'	75°50'	0.70	(1)
7		40°06'	77°11'	0.57	(1)
1	South Carolina	34°32'	80°45'	1.05	(2)
2		34°19'	81°09'	1.47	(2)
3		34°10'	81°02'	1.09	(4)
4		33°55'	82°07'	1.62	(2)
5		33°55'	81°10'	1.11	(4)
6		33°17'	81°40'	1.06	(1)
1	Tennessee	36°05'	83°39'	0.83	(4)
2		35°55'	84°19'	0.82	(1)
3		35°34'	84°29'	1.01	(4)
1	Texas	31°55'	106°00'*	11.0	(6)
2		31°55'	106°00'*	7.0-8.0	(6)
3		31°45'	106°30'*	2.0	(6)
4		31°39'	102°15'	1.2	(1)
5		31°27'	104°53'	1.0	(1)
6		31°23'	101°48'	1.1	(1)
7		31°15'	101°28'	1.1	(1)
8		31°12'	101°29'	2.0	(1)
9		31°10'	103°14'	1.1	(1)
10		29°48'	104°24'	1.5	(1)
11		29°07'	99°41'	1.11	(1)
1	Vermont	43°20'	72°33'	1.20	(1)
2		43°17'	72°49'	1.22	(1)
3		43°15'	72°50'	1.23	(1)
1	Virginia	37°46'	78°06'	0.97	(2)
2		37°20'	82°00'	1.7	(1)
3		36°52'	77°54'	1.4	(1)
4		36°50'	77°19'	1.24	(2)

*Location approximate.

TABLE 2 (concluded)

HEAT FLOW VALUES IN THE EASTERN UNITED STATES

	State	Location Lat.(N)	Long.(W)	Heat Flow ($cal/cm^2 sec$)	Reference
5	Virginia	36°49'	81°06'	1.03	(1)
6		37°58'	75°36'	1.8	(2)
7		37°57'	75°27'	1.85	(2)
8		37°53'	76°15'	1.4	(2)
9		37°43'	75°43'	1.3	(2)
10		37°18'	75°56'	1.4	(2)
11		37°04'	76°20'	1.2	(2)
12		36°57'	76°16'	1.3	(2)
13		36°55'	76°42'	1.1	(2)
14		36°51'	76°29'	1.4	(2)
1	West Virginia	39°40'	79°59'	1.2	(1)
2		39°25'	80°05'	1.20	(1)
3		39°18'	80°14'	1.26	(1)
4		39°17'	80°46'	1.22	(1)

References: (1) Sass and others, 1976; (2) Costain and others, 1979; (3) Smith and others 1978; (4) Smith and others, 1979; (5) Smith and Griffin, 1977; (6) Rob Roy, personnel communication, 1979.

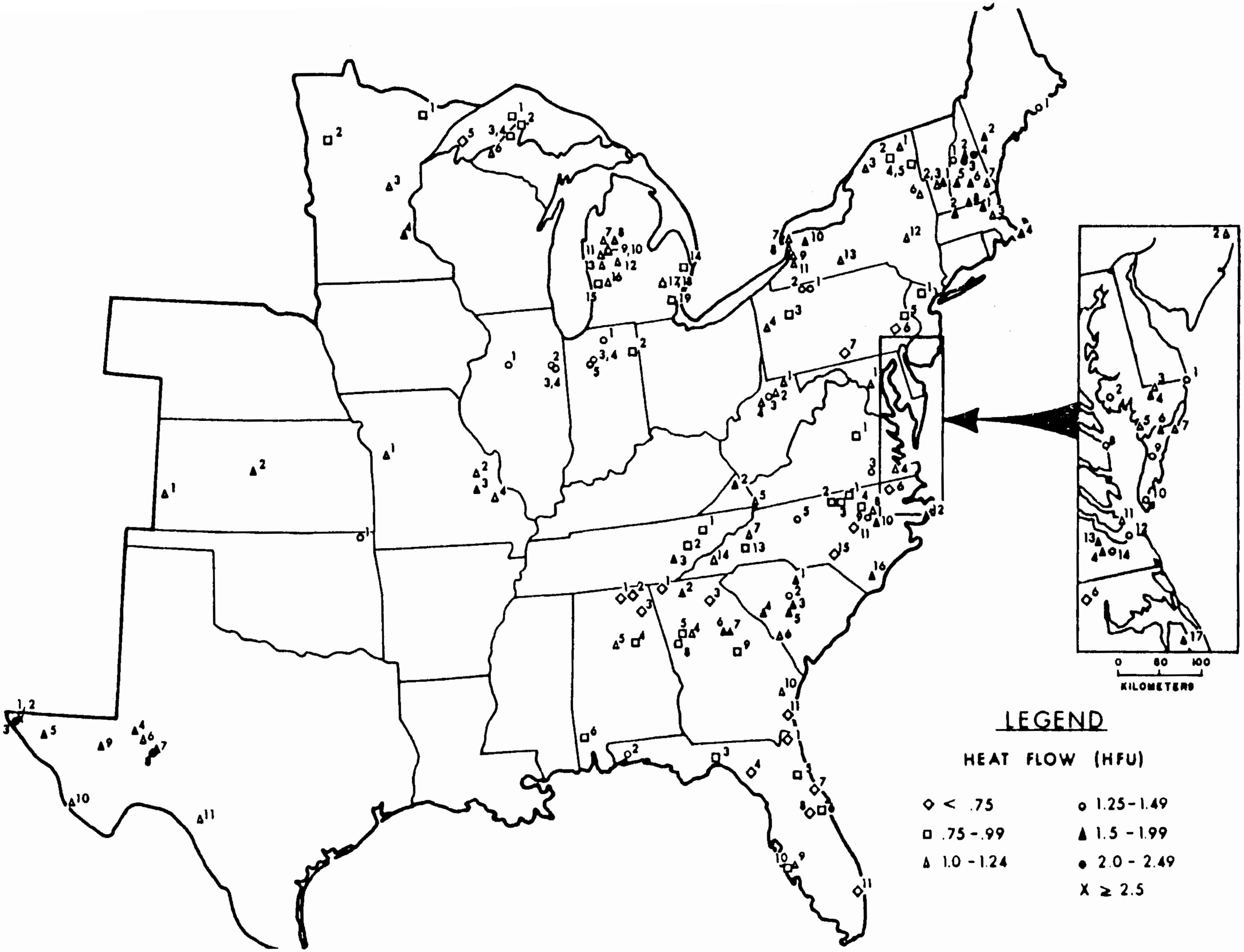


Figure 7.-- Heat flow values in the eastern United States.
The numbers refer to Table 2.

that heat flow values in the eastern United States are usually less than about 1.5 HFU. Exceptions are areas of New England, the Piedmont, and the Atlantic Coastal Plain related to radioactive plutons; certain small areas in south central New York state; and some areas in the Basin and Range portion of Texas. Interpretation of the significance of the high heat flow values in western Texas has not yet been completed, but upward movement of water and the consequent upward transfer of heat probably plays an important role (Rob Roy, personal communication, 1979).

The data currently available provide a good estimate of the regional character of heat flow in the eastern United States. However, some presently unknown regions of high heat flow might be detected by investigation of postulated radioactive plutons in the basement. Such plutons would most likely be of Precambrian or Paleozoic age, but because uranium and thorium decay very slowly, they could provide significant thermal energy, given sufficiently high concentrations of radioactive elements.

Inferences about geothermal resources can be made by examination of the temperature gradient imposed on an area by heat flow and thermal conductivity. Numerous subsurface temperature measurements have been made in the eastern half of the country in the course of petroleum exploration. Recently, the American Association of Petroleum Geologists and the U.S. Geological Survey (1976a,b) have jointly published several maps showing regional variations in subsurface temperatures. The first map, a simplified version of which is shown as Fig. 8, gives average temperature gradients calculated from drill hole information; a second map shows, where data are available, the depth to various isothermal surfaces. These maps, however, have only limited usefulness for geothermal exploration. The bottomhole temperatures used to calculate gradients and the corrections applied to them may introduce errors. Moreover, since the maps were not prepared with geothermal exploration in mind, anomalously high gradients were not taken into account.

Review of data from the Michigan basin shows 20 wells with uncorrected gradients greater than 36.4°C/km (2°F/100 ft). All but three of these wells are less than 900 meters (3,000 feet) deep. Deeper wells in Michigan provided gradients closer to 20°C/km (1.1°F/100 ft). Thus, well depths seem to be negatively correlated with geothermal gradients. At least two mechanisms may be responsible for this observation: shallow wells in Michigan may be drilled through proportionately greater thicknesses of poorly conductive rocks than deeper wells, or shallow wells may be more likely to yield errors in temperature measurement. A careful review of the data will be necessary before definite conclusions can be reached.

Comparison of the temperature gradient map with the map showing approximate thickness of sedimentary rocks (Fig. 5) indicates that the highest gradients are generally associated with the marginal areas of the interior basins rather than with their deeper parts. An exception is the Gulf Coast region; in this case, upward movement of waters from deep geopressured reservoirs is suspected. Updip movement of fluids may also be responsible for the association of higher gradients with basin margins elsewhere.

Despite these problems, the data set from which the gradient map was generated is the best currently available for study of geothermal phenomena in

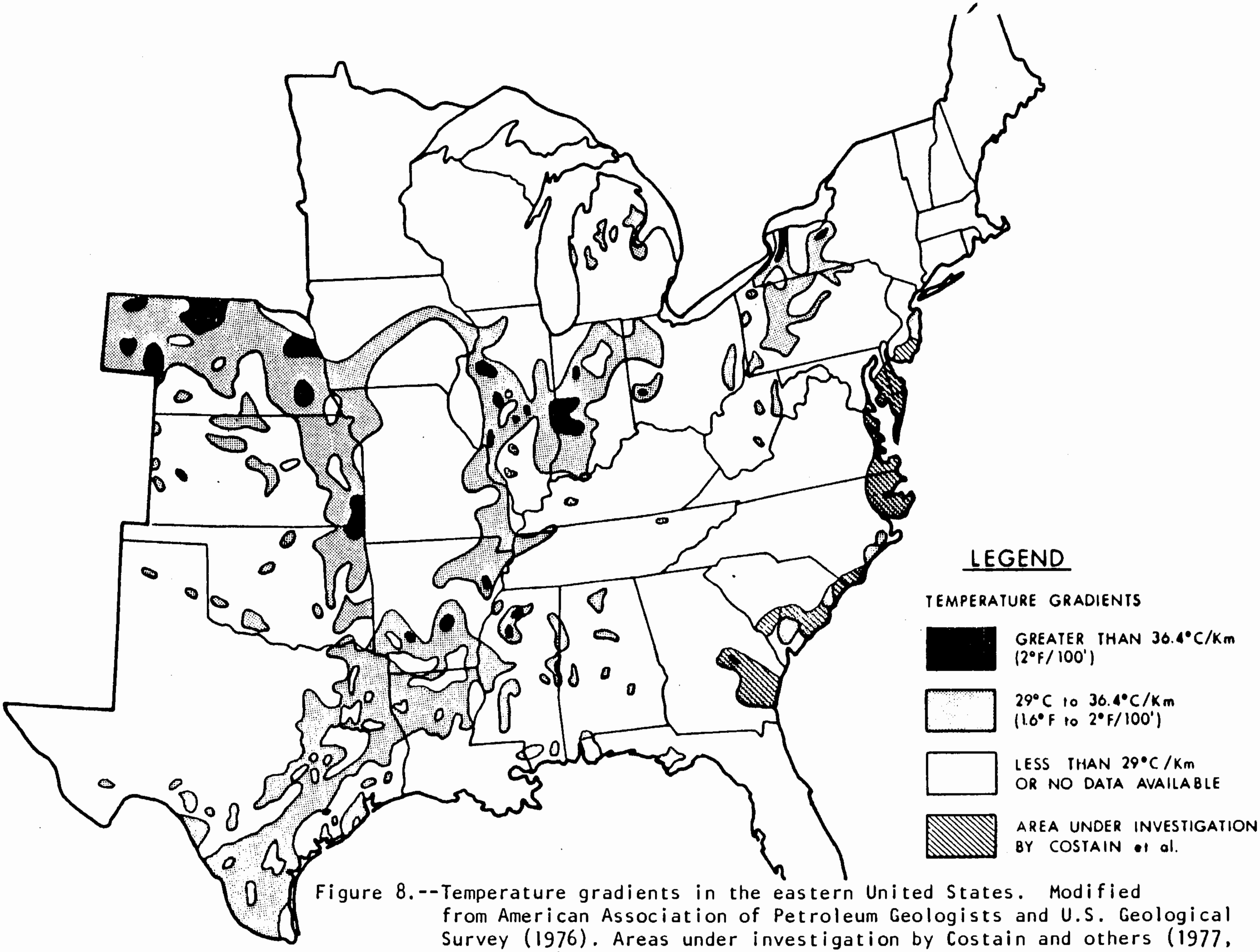


Figure 8.--Temperature gradients in the eastern United States. Modified from American Association of Petroleum Geologists and U.S. Geological Survey (1976). Areas under investigation by Costain and others (1977, 1978, 1979) are also shown.

the eastern United States. The Los Alamos Scientific Laboratory is using the gradient data to target hot dry rock exploration in the east. Preliminary results are encouraging and suggest that some of the anomalies may be more important than the gradient map implies (Maxwell, 1979, and personal communication). Further studies should be made, particularly comparisons of temperature gradients with hole depths and gross lithology types.

If heat flow, conductivity values, and sediment thickness are known, changes of temperature with depth and estimated temperatures at the base of the sedimentary section can be calculated. The results of several such calculations are shown graphically in Fig. 9. Heat flows reported by Sass and others (1976) in the eastern United States generally range from 1 to 2 heat flow units. Diment and others (1975) propose a conductivity (K) of 6×10^{-3} cal/cm sec °C as representative of a thick sequence of crustal rocks. Under these conditions, and with an average surface temperature of 10°C (50°F), temperatures between 35° and 60°C (95° and 140°F) can be reached at a depth of 1,500 meters (4,900 feet).

Caution must be exercised in all cases where gradients are used to project temperatures below the depth of measurement. Temperature gradients vary with rock type, and they may be affected by vertical movement of fluids. In general, conductivities increase with depth, so that gradients decrease with depth. Thus, linear projection of gradients below observation points may predict temperatures much higher than those which actually exist.

Geochemistry. The geochemistry of warm springs is an important key to subsurface water temperatures (White, 1970).

Chemical analysis of waters from springs and geothermal wells yields data from which most predictions of subsurface water temperatures are made. Temperatures can be calculated from chemical analyses because the concentrations of chemical species dissolved in the water vary directly with temperature. The principal methods used are the silica geothermometer (Fournier and Rowe, 1966) and the sodium-potassium-calcium geothermometer (Fournier and Truesdell, 1973).

Several conditions must be met if reservoir temperatures are to be estimated from the chemistry of warm springs. The most important requirements, discussed more completely by Fournier and others (1974), are:

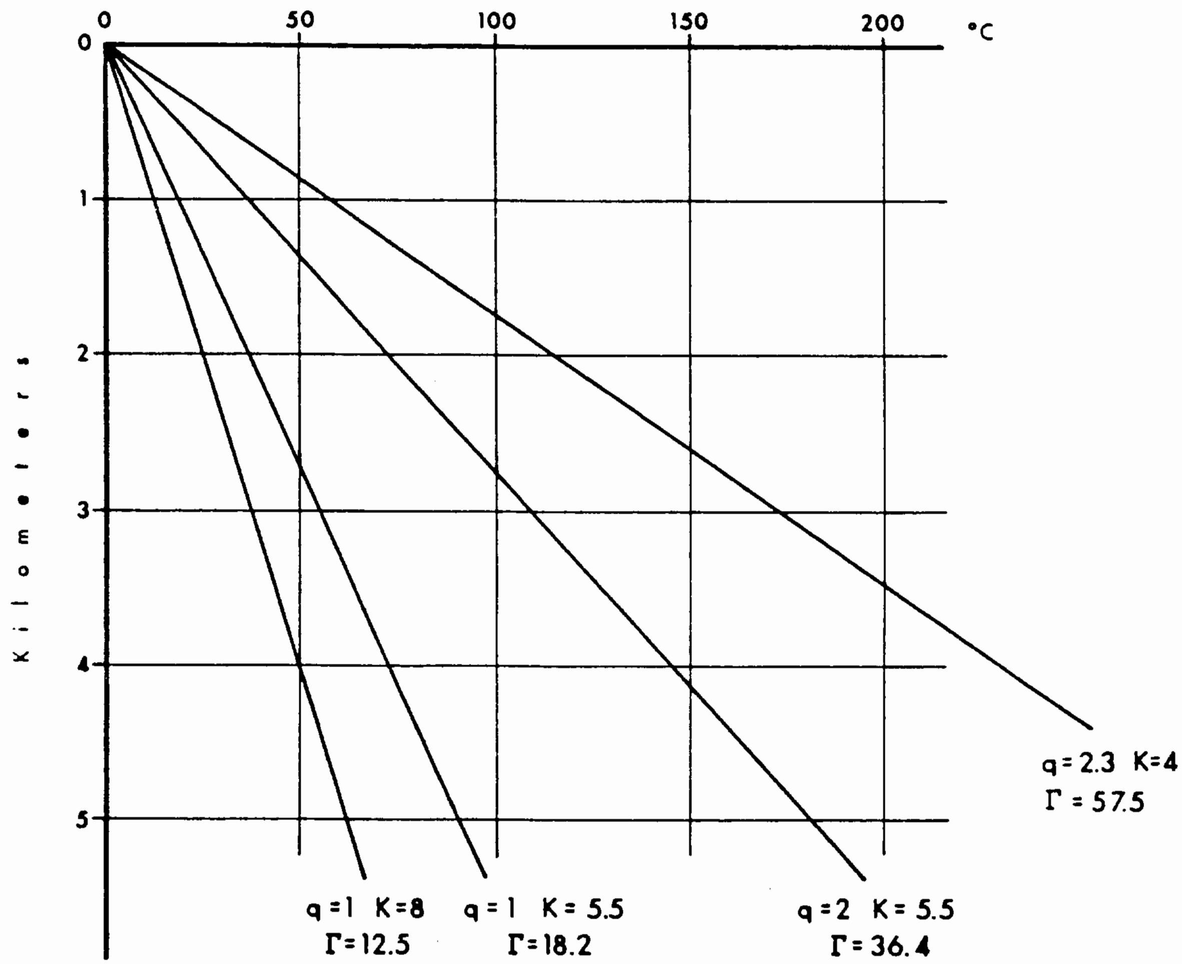
1. Temperature-dependent reaction and equilibration occur at depth.

2. The necessary constituents for the assumed temperature-dependent reaction are available in excess of that necessary for equilibrium.

3. Little or no re-equilibration occurs as the water flows to the surface.

4. The waters are not mixed with shallower ground water while coming to the surface.

Commonly, these restrictions are met in the high- to moderate-temperature geothermal systems of the west. However, because the geochemical temper-



-ure 9.--Temperature increase with depth. Heat flow and average conductivity (K) are as specified. The slope of line (Γ) is calculated from the equation $q=K\Gamma$. The lines show a reasonable minimum conductive gradient (Γ=12.5°C/km), an average stable continental gradient (Γ=18.2°C/km), a gradient twice the average (Γ=36.4°C/km), and a reasonable maximum gradient (Γ=57.5°C/km) for the eastern United States. Approximate subsurface temperatures can be obtained by adding the appropriate mean surface temperature to values obtained from this chart.

ature scales were chiefly developed from studies of high-temperature thermal systems, the reactions assumed in establishing the geothermometers may not reach equilibrium in the lower temperature systems encountered in the eastern United States.

The silica geothermometer is generally the more reliable at lower temperatures. However, since the principal forms of silica--quartz and chalcedony--have different solubilities, the user must have some idea of which of the two possible equilibria predominates within the reservoir. In low-temperature systems, chalcedony is usually selected (Sammel, 1979) and the geochemical temperatures given in Table 3 for warm springs in the east are generally based on the chalcedony equilibrium.

The other common geothermometer depends on the relative proportions of sodium, potassium, and calcium found in geothermal waters (Fournier and Truesdell, 1973). The method was developed by correlating measured temperatures of geothermal reservoirs with chemical data. The temperature scale is sensitive to calcium concentration, which in turn is quite sensitive to the concentration of dissolved carbon dioxide (CO_2). Reactions in the system $CaCO_3$-CO_2-H_2O are rapid, and re-equilibration occurs with ease. Loss of CO_2 from solution, with consequent deposition of calcite ($CaCO_3$) and readjustment of the relative proportions of sodium, potassium, and calcium, makes utilization of the Na-K-Ca geothermometer difficult in many systems. Interpretation is particularly difficult in areas where CO_2 is lost at spring orifices.

Swanberg and Morgan (1978) have developed a correlation between temperatures based on the silica content of groundwater and regional heat flow. Their approach to the study of silica in groundwater should provide a valuable reconnaissance tool in the search for geothermal resources in the Eastern United States.

Chemical data in the U.S. Geological Survey water quality data bank WATSTORE were used to calculate silica geotemperatures for groundwaters in the United States. The results were presented as a series of histograms showing the distribution of temperature within each of several major physiographic divisions. The mean silica temperature for a province was then plotted against the heat flow (q) for the province, where both parameters were well defined. Temperatures based on the silica geothermometer are indicated here by the symbol $T(SiO_2)$. The plot resulted in the linear correlation $T(SiO_2) = mq + b$. It is thought that the slope m multiplied by thermal conductivity K provides a clue to the mean depth of ground water circulation. Depths of 1.4 and 2.0 kilometers (4,600 and 6,560 feet) are implied for sediments and crystalline rocks, respectively (Swanberg and Morgan, 1978). It is interesting that temperatures for the ground waters sampled correlate well with regional heat flow and do not seem to be appreciably affected by average air temperatures in any given province. Possibly this is the result of the relatively deep source of fluids implied by the model. Such a depth should yield water temperatures about 25° to 36°C (45° to 65°F) above average air temperatures in the conterminous 48 states.

Swanberg and Morgan also averaged the silica geotemperatures over a 1° x 1° grid and contoured the results. The map shows regional trends in temperature variation quite similar to regional heat flow patterns. Presumably a finer grid would provide more detail in areas of particular interest.

Seismic Activity. Major high-temperature convective hydrothermal systems are usually associated with tectonic activity. Most major seismic events also occur in areas of major tectonic activity (spreading ridges, subduction zones, and continental rift zones, in the parlance of continental drift). The eastern United States is generally regarded as tectonically stable; however, some seismicity remains. Because of the close association worldwide between hydrothermal phenomena and seismicity, it is expected that seismically active areas in the eastern United States might have above-average potential for geothermal resources.

Hadley and Devine (1974) have published a seismotectonic map of the eastern United States relating historical seismic activity (1800-1972) and geologic structures. Stover (1977) has prepared a seismicity map for the period 1965-1974. Both maps show generalized tectonic features. However, Stover's map is based on seismic records for such a limited time period that prediction of seismic zones is difficult, and the map prepared by Hadley and Devine covers only the area east of the Mississippi River.

Woollard (1958, 1969) points out several possible zones of seismic activity. The geochemical survey of Swanberg and Morgan (1978) and the temperature gradient map of the American Association of Petroleum Geologists and U.S. Geological Survey (1975) show some correlation with the zones proposed by Woollard. Zones and epicenters from the above sources are shown in Fig. 10.

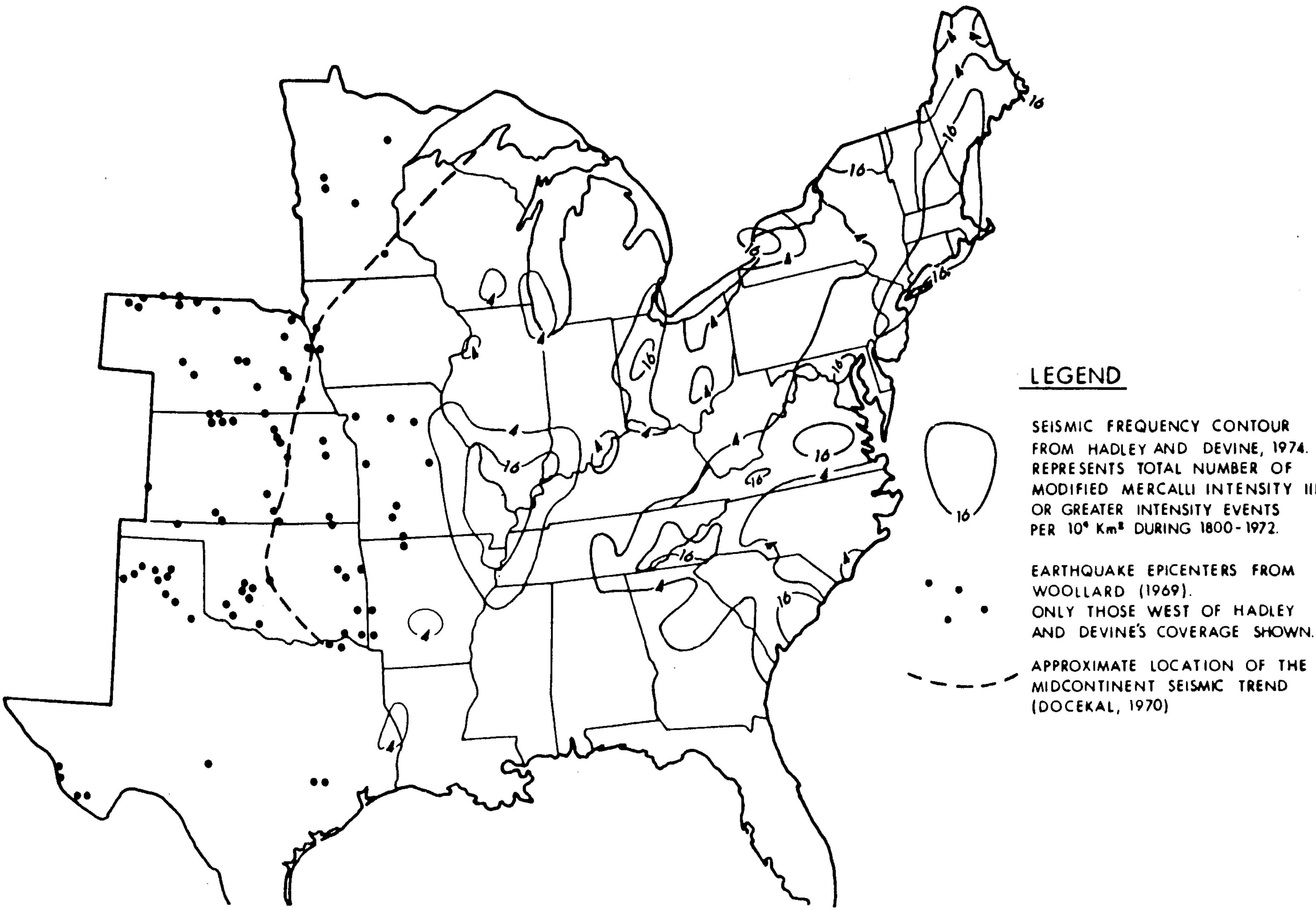


Figure 10.--Historic seismic activity and seismic zones. Modified from Woollard (1969), Hadley and Devine (1974), and Docekal (1970).

Areas of Indicated Geothermal Potential

A refined and updated assessment of U.S. geothermal resources has recently been published (Muffler, 1979). As does an earlier assessment (White and Williams, 1975), this shows that systems related to igneous rocks and hydrothermal convection systems with temperatures of 90°C (194°F) or more are found only in the western United States. The 1979 report, however, includes a comprehensive summary of locations where low-temperature thermal waters are known to be present near the surface in the eastern United States. Also listed are several areas where the existence of subsurface thermal waters has been inferred.

The known occurrences of geothermal energy in the eastern states can be divided into four categories:

1. Warm spring systems,

2. Radioactive, heat-producing granite plutons beneath a thick covering of poorly conducting sediments,

3. Aquifers containing abnormally warm waters, and

4. Deep sedimentary basins with normal geothermal gradients.

These are discussed below.

Warm Springs

Thermal springs have been reported in the eastern United States since colonial times. Nearly all early descriptions dwelt on their therapeutic and recreational values (Crook, 1899; Fitch, 1927; Moorman, 1867). All early data sources contain inaccuracies due to changes in spring character through time, uncertain locations, and, to an unknown extent, inaccurate temperature data.

Peale (1886) provides the most comprehensive early listing of mineral springs in the United States, and his compilation is still a valuable guide to warm spring locations. The most truly encyclopedic listing and today's best source of information on thermal springs of the United States was published by Waring in 1965. The present discussion relies on modern reports or older accounts that have been verified at least in part. The principal sources used are Hobba and others (1976), Sammel (1979), Waring (1965), and Berry (personal communication, 1979).

Thermal springs are defined in various ways. Waring (1965, p. 4) labels as "thermal" those springs with temperatures "at least 15°F [8°C] above the mean annual temperature at their localities," with some adjustment for areas of low and high mean annual temperature. Sammel (1979, p. 87) opts for temperatures greater than 10°C (18°F) above mean ambient temperature as a cutoff, in substantial agreement with Waring.

In general, this report adopts Sammel's definition. The locations and other site-specific information on eastern springs are listed in Table 3.

Locations are also shown in Fig. 11.

No comprehensive reports on the geochemistry and geothermometry of eastern warm springs exist. Chemical analyses, however, are available for most of the important springs. Hobba and others (1976) analyzed the more important springs in the Appalachians. Their data provide the most reliable measurements for geothermometry available in the region. A discussion of the results of their study is currently in press (Hobba and others, 1978).

Bedinger and others (1979) discuss the geology and geochemistry of Hot Springs National Park, Ark.

Table 3 also lists analytical data from published reports and equilibrium temperatures calculated for this report, together with minimum equilibration temperatures proposed by Sammel (1979). In some instances the reservoir temperatures derived from geochemistry are lower than the surface temperatures of the springs. In these cases it is likely that interpretation of the geochemical data is in error due to mixing of thermal water with cool water or equilibration with minerals other than those assumed in the geochemical model. Much of the scatter in the Na-K-Ca derived temperature estimates may be due to deposition of calcite near the spring outlet or to the influence of saline formation waters.

Geochemical considerations suggest that reservoir temperatures are not substantially higher than measured surface temperatures at most eastern thermal springs, a reasonable inference in view of the generally average continental heat flow in the area. These estimated temperatures correspond to maximum circulation depths slightly greater than 3 kilometers (10,000 feet) in areas of average geothermal gradient. Although not all of the warm springs fall into the provisional classification of low-temperature resources--subsurface temperatures of 40°C (104°F) or more within 1 kilometer (3,300 feet) of the surface--they are generally suitable for small-scale, direct-use applications such as swimming pool or space heating.

<u>Appalachian thermal spring model</u>. The warm springs of the eastern states, except for those in Alabama, Florida and western Texas, are found either in the Appalachians or in the geologically similar Ouachita Mountains.

Much has been written about the structural control of warm springs in the Appalachians. Few major changes, however, have been made to the model of deep circulation in folded and faulted rocks originally proposed by Rogers (1884).

Modern work on the origin of "Appalachian" type warm springs is currently under way in Virginia (Costain, 1979) and Arkansas (Maxwell, 1979). The geologic settings of both areas are similar. Review of additional publications on these areas (Bedinger and others, 1979; Purdue and Miser, 1923; Rogers, 1884; Reeves, 1932; Rodgers, 1970; Geiser, 1976; Dennison and Johnson, 1971) and of the geology of other Appalachian warm springs (Massachusetts and New York: Zen, 1967; Pennsylvania: Dyson, 1967; North Carolina: Oriel, 1950, Stose and Stose, 1947; Georgia: Hewett and Crickman, 1937)

TABLE 3

THERMAL SPRINGS OF THE EASTERN UNITED STATES

	Spring	Location lat (N)	Location long (W)	Surface temperature, °C	Chemical analysis ppm SiO_2	Ca	Na	K	Estimated Reservoir Temperature, °C* Quartz Conductive	Chalcedony	$Na-K-\frac{1}{3}Ca$	$Na-K-\frac{4}{3}Ca$	Minimum Equilibration Temperature	Source**
	ARKANSAS													
1	Warm Springs	36°28.8'	91°03.0'	28	-	-	-	-	-	-	-	-	-	(a)
2	Big Chalybeate Spring	34°32.4'	93°01.2'	26	-	-	-	-	-	-	-	-	-	(a)
3	Hot Springs	34°30.6'	93°03.2'	64	42	45	4	1.5	94	62*	177	4	64	(b)
4	Spring on Little Missouri River	34°24.4'	93°54.5'	23	-	-	-	-	-	-	-	-	-	(a)
5	Caddo Gap Springs	34°23.0'	93°36.4'	35	19	42	3.3	0	62	27*	-	-	-	(b)
6	Spring on Redland Mt.	34°19.3'	93°44.3'	25	-	-	-	-	-	-	-	-	-	(a)
	FLORIDA													
1	Warm Mineral Springs	27°03.6'	82°15.7'	30	16	500	5200	150	56	21*	148	184	30	(i)
2	Little Salt Spring	27°04.4'	82°14.0'	27	19	180	750	23	62	27*	130	101	-	(i)
	GEORGIA													
1	Warm Springs	32°53.6'	84°41.4'	31	20	22	1.2	3.8	64	29*	304	26	34	(d)
2	Parkman Spring	32°51.7'	84°39.0'	25	-	-	-	-	-	-	-	-	-	(a)
3	Tom Brown Spring	32°52.4'	84°32.8'	20	-	-	-	-	-	-	-	-	-	(a)
4	Thundering Spring	32°57.8'	84°29.9'	24	-	-	-	-	-	-	-	-	-	(a)
5	Barker Spring	32°55.2'	84°26.3'	23	-	-	-	-	-	-	-	-	-	(a)
6	Lifsey Spring	33°02.2'	84°22.4'	26	-	-	-	-	-	-	-	-	-	(a)
7	Taylor Spring	33°01.1'	84°19.6'	24	-	-	-	-	-	-	-	-	-	(a)
	MASSACHUSETTS													
1	Sand Spring	42°44.1'	78°12.0'	24	12	25	2.0	0.9	46*	11	180	-3		(e)
	NEW YORK													
1	Lebanon Spring	42°28.8'	73°22.2'	22	12	35	6.9	1.2	46*	11	150	7	51	(d)

*Best geochemical estimate of reservoir temperature shown by asterisk; minimum equilibrium temperatures are taken from Sammel (1979). Discrepancies between surface and reservoir temperatures are probably due to errors in interpretation of geochemical data; see p. 37.

**See end of table.

TABLE 3 (cont.)

THERMAL SPRINGS OF THE EASTERN UNITED STATES

	Spring	Location lat (N)	long (W)	Surface temperature, °C	Chemical Analysis ppm SiO_2	Ca	Na	K	Estimated Reservoir Temperature, °C * Quartz Conductive	Chalcedony	Na-K-$\frac{1}{3}$Ca	Na-K-$\frac{4}{3}$Ca	Minimum Equilibrium Temperature	Source**
		NORTH CAROLINA												
1	Hot Springs	35°53.8'	82°49.6'	42	31	135	10	10	81	48*	245	37	50	(d)
		PENNSYLVANIA												
1	Perry County Warm Springs	40°19.7'	77°14.8'	18	9	38	1.6	0.5	37*	1	154	-20	36	(d)
		TEXAS												
1	Red Bull Spring	30°51.7'	105°20.4'	37	36	15.5	312	11	88	54*	14	125	56	(f)
2	Indian Hot Sprgs.	30°49.4'	105°18.9'	47	40	150	2185	134	92	59*	182	207	60	(f)
3	Capote Warm Sprg.	30°12.6'	104°33.7'	37	37	1.6	120	0.6	89	56*	70	64	57	(f)
4	Nixon Springs	30°08.0'	104°36.1'	32	43	20.5	160	5.5	95	63*	128	84	60	(f)
5	Ruidosa Hot Springs	30°02.3'	104°35.9'	45	35	27.5	148	14.5	86	53*	174	111	55	(f)
		29°48.3'	102°22.6'	32										
6	Las Cienegas	29°47.2'	104°27.7'	30	39	27	228	6	91	58*	120	84	60	(f)
7	Hot Springs	29°10.9'	102°59.5'	41	22	133	108	5.8	68*	33	328	157	41	(f)
8	Rio Grande Village Spring	29°10.7'	102°57.2'	36	21	125	98	5.4	66	31	0.29	43*	36	(f)
		VIRGINIA												
1	Bragg Spring	38°14.3'	79°39.0'	24	-	-	-	-	-	-	-	-	-	(a)
2	Bolar Spring	38°13.1'	79°40.4'	23	11	58	1.6	2.3	43*	8	238	3	30	(d)
3	Warm Springs	38°03.3'	79°46.8'	35	21	112	3.7	7.4	66*	31	274	25	41	(d)
4	Hot Springs	37°59.8'	79°49.8'	41	21	132	7.0	13	66	31	283	42*	41	(d)
5	Healing Springs	37°57.8'	79°51.7'	30	24	118	6.5	2.4	71	37*	176	4	43	(h)
6	Rockbridge Baths	37°53.9'	79°27.7'	22	-	-	-	-	-	-	-	-	-	(a)
7	Layton Springs	37°51.6'	79°59.3'	22	-	-	-	-	-	-	-	-	-	(a)
8	Falling Spring	37°52.2'	79°56.0'	25	18	158	3.8	16	60	25	336	39*	40	(d)
9	Sweet Chalybeate Spring	37°38.7'	80°14.3'	24	-	228	17.9	24.5	-	-	274	53*	-	(c)
10	New River White Sulphur Springs	37°17.4'	80°37.1'	29	-	-	-	-	-	-	-	-	-	
11	Alum Springs	37°09.6'	80°48.4'	22										

*Best geochemical estimate of reservoir temperature shown by asterisk; minimum equilibrium temperatures are taken from Sammel (1979). Discrepancies between surface and reservoir temperatures are probably due to errors in interpretation of geochemical data; see p. 37.

** See end of table.

TABLE 3 (cont.)

THERMAL SPRINGS OF THE EASTERN UNITED STATES

	Spring	Location lat (N)	long (W)	Surface temper-ature, °C	Chemical Analysis ppm SiO_2	Ca	Na	K	Estimated Reservoir Temperature, °C * Quartz Conductive	Chalcedony	$Na-K-\frac{1}{3}Ca$	$Na-K-\frac{4}{3}Ca$	Minimum Equilibrium Temperature	Source**
		WEST VIRGINIA												
1	Berkeley Springs	39°37.1'	78°13.8'	22	9.5	45	4.1	1.0	38*	3	156	-4	38	(d)
2	Swan Pond Spring	39°28.3'	77°52.6'	22	-	-	-	-	-	-	-	-	-	(S)
3	Thorn Spring	38°36.3'	79°21.2'	22	-	-	-	-	-	-	-	-	-	(S)
4	Minnehaha Springs	38°09.8'	79°58.5'	21	14	61	4.2	0.4	51*	16	113	-24	34	(d)
5	Old Sweet Spring	37°37.8'	80°14.4'	23	18	-	-	-	-	-	-	-	-	(g)

*Best geochemical estimate of reservoir temperature shown by asterisk; minimum equilibrium temperatures are taken from Sammel (1979). Discrepancies between surface and reservoir temperatures are probably due to errors in interpretation of geochemical data; see p. 37.

**(a) Berry, personal communication, 1979; (b) Bedinger and others, 1979; (c) Helz and Sinex, 1974; (d) Hobba and others, 1976; (e) Hansen and others, 1974; (f) Henry, 1977; (g) Price, 1936; (h) Reeves, 1932; (i) Rosenau and others, 1977.

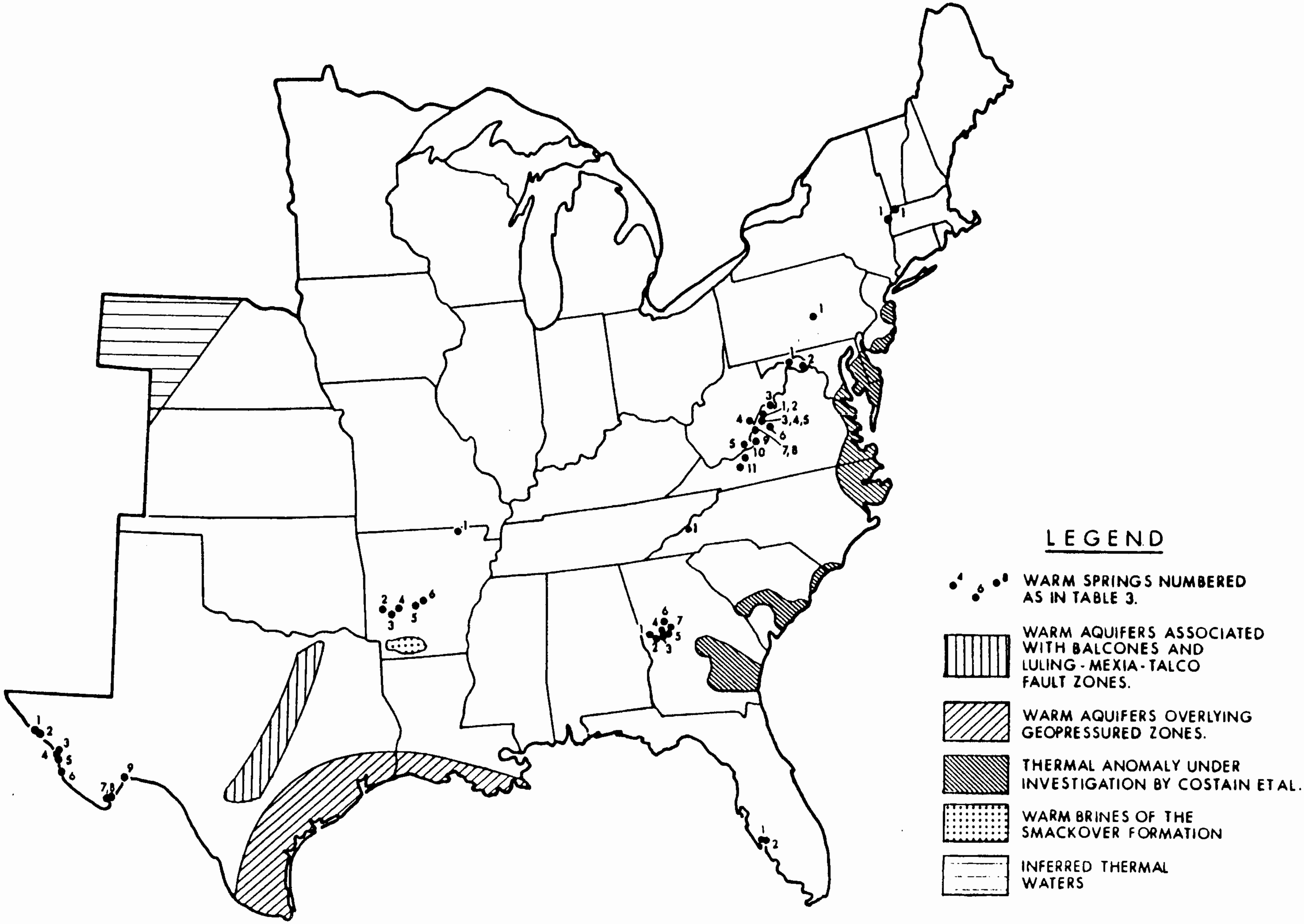


Figure 11.-- Areas of indicated geothermal resources.

suggests that all warm springs in the Appalachian and Ouachita regions have similar origins, despite the substantial distances separating them.

Costain (1979) notes the coincidence of water gaps, warm springs, and steeply dipping quartzite beds in Virginia and postulates that groundwater enters Silurian quartzites or carbonates, descends to depths sufficient to be heated, and then rises rapidly along east-west fracture zones cutting the Warm Springs anticline. Steeply dipping siliceous rocks are also present at Hot Springs, N.C., Warm Springs, Ga., and Hot Springs, Ark. Although transverse fractures are not known to be associated with the springs in these areas, the alignment of the French River near Hot Springs, N.C., suggests the presence of a fault.

No detailed geologic studies of Sand Springs in Massachusetts or Lebanon Springs in New York are available. Their proximity to the Taconic structures described in Zen (1967) suggests that the rocks from which these springs discharge (particularly Lebanon Springs) may be structurally similar to those of the Folded Appalachians, although the relationships are unclear because of the Taconic and succeeding periods of orogeny.

The importance of fault control to Appalachian warm springs is not clear. Faulting is present in all of the hot spring areas of the Appalachian and Ouachita mountains but no springs are known to discharge in fault zones, except those inferred by studies of linears.

Warm springs and faults. Warm springs in the Basin and Range province are commonly found in or near fault zones. Many fault zones, however, are silicified and filled with gouge; the older a fault system, the more likely sealing has occurred. Faults in the Basin and Range province associated with thermal springs are relatively young on a geologic time scale. In fact, there is some evidence that recurrent seismic activity is necessary to maintain thermal springs. Swanberg and Morgan (1978) note that ground waters in the eastern United States are characterized by low silica temperatures, except in tectonically active areas like New Madrid, Mo., southern New York, and South Carolina.

Many currently inactive fault systems in the east, such as the Rough Creek zone in Illinois and Kentucky and the border faults of the Triassic basins, are not associated with obvious thermal anomalies. Rodgers (1970) notes that silification is common in the Triassic border faults, suggesting that movement of silica-rich thermal solutions may have been important in the past.

Faults as old as those of the Appalachians and Ouachitas have had ample time for any original permeability to be closed off. Recent faulting in relatively brittle, clean-fracturing quartzites may allow permeability to be maintained, however. Possibly this is important in the Warm Springs, Va., area through which the 38th parallel lineament is thought to extend and perhaps to be still active (Dennison and Johnson, 1971). Quartzite beds are also present there.

Absence of thermal anomalies where old fault systems occur may be due to other hydrologic conditions. Steeply inclined beds forming recharge zones and topographic lows to localize discharge may be necessary for the development of thermal convection systems.

Other eastern thermal springs. The springs in the Trans-Pecos region of Texas have higher indicated geochemical temperatures than any other thermal springs in the east except those at Hot Springs, Ark. They appear to be associated with Basin and Range style faulting and with the Rio Grande rift (Henry, 1977 and 1979). Henry (1977) lists several wells in the area that have produced abnormally warm waters at shallow depths. The Brisco well in the Presidio Bolson encountered a temperature of about 51°C (124°F) at 27 meters (90 feet). In a Gulf Oil Company well north of Presidio Bolson, 82°C (180°F) water was reported at 874 meters (2,870 feet). Near Terlingua, two occurrences of water at about 45°C (113°F) are recorded at 270 meters (880 feet).

Thermal springs in Florida appear to be caused by the local upwelling of thermal waters originating in the Floridian aquifer. Kohout and others (1977) believe the springs to be the result of convection cells involving heating of sea water as it moves inland along the Floridian Plateau. This model is questioned, but not entirely ruled out, by Sproul (1977). In any event, the waters are not much warmer than the average air temperature in Florida.

Radioactive, Heat-Producing Granitic Plutons

Radioactive, heat-producing granitic plutons buried beneath thick blankets of minimally conductive sediments may provide the best source of geothermal energy along the Atlantic Coast of the United States. Costain and others (1976) are continuing to study this potential resource. Their reports give a detailed account of the theoretical model and the validation procedures used. Only a brief summary of their approach and major results is given here.

Numerous granitic plutons, somewhat richer in uranium and thorium than the surrounding rocks, have been observed in the Piedmont. Similar plutons are thought to exist beneath much of the Atlantic Coastal Plain. Although the concentrations of uranium and thorium are not high--10 ppm of uranium (Glover, 1979) and three to four times as much thorium (Costain, 1979)--enough of these elements is present in many plutons of the Piedmont for elevated heat flows to be observable above buried plutons. Temperature gradients as high as 48°C/km (2.6°F/100 ft) have been recorded in a series of shallow (300-m, 1,000-ft) holes drilled in the Atlantic Coastal Plain above possible plutons inferred from gravity and magnetic data (Costain, 1979).

The thicker the sedimentary cover over a pluton, the higher the temperature expected at the base of the sedimentary sequence. The interrelationships of temperature, depth, thickness of sediments, and heat flow are shown in Fig. 9.

A 1,500-meter (5,000-foot) well drilled near Crisfield, Md., has partially confirmed the Costain model. The 56°C (133°F) water produced from the well at 1.2 kilometers (4,000 feet) depth is subeconomic at present, but has a strong potential to be economic in the not-too-distant future. The locations of temperature and gravity anomalies on the Atlantic Coastal Plain possibly associated with similar or higher-grade geothermal resources are shown in Figs. 8 and 11. The availability in these areas of thermal waters in sufficient quantity for production is not yet confirmed.

Buried granitic plutons may provide heat not only for hydrothermal systems in the overlying sediments but also for hot dry rock systems within the plutons. Los Alamos Scientific Laboratory is currently investigating this possibility.

Abnormally Warm Aquifers

Abnormally warm aquifer water is known or inferred to exist in several areas of the eastern United States. The largest region with this potential lies in Texas and Arkansas in the Ouachita structural belt and in the Balcones and Luling-Mexia-Talco fault zones. Numerous warm-water wells have been drilled here, and measured geothermal gradients range from 25 to 45°C/km (1.4 to 2.5°F/100 ft) within 1 kilometer (3,300 feet) of the surface (Sammel, 1979). Studies are underway to assess more fully the potential of the area and to accelerate development. These and other studies have focused on Cretaceous aquifers within the fault zones or overlying the buried Ouachita structural belt (Woodruff, 1978). The warm waters are probably related to upward migration along fault zones or updip within the Cretaceous sediments.

Complicating the picture in the northern Gulf of Mexico Basin is the presence of geopressured-geothermal reservoirs in almost all Cenozoic formations and some deep Mesozoic rocks (Wallace and others, 1979). Although these reservoirs are not a subject of this report, Sammel (1979) suggests that they may be responsible for elevated temperatures in a broad zone of shallow aquifers possibly extending from South Texas to Alabama. These aquifers, generally Tertiary in age, lie east of the major fault zones and the Ouachita structural belt with which the thermal waters in the Cretaceous rocks of eastern Texas are associated.

The third known occurrence of thermal waters in the eastern United States is an extensive thermal brine field in southern Arkansas. Numerous wells in the Smackover Formation exhibit gradients in the 30 to 40°C/km (1.6 to 2.2°F/100 feet) range at depths of 1 to 3 kilometers (3,300 to 10,000 feet) (Collins, 1974). According to Sammel (1979) the maximum temperatures measured in the deepest wells are about 140°C (284°F).

The existence of an extensive area of thermal waters, an extension of the thermal field of western South Dakota, is inferred under the western third of Nebraska (W. D. Gosnold, personal communication 1979). The Nebraska Conservation and Survey Division is beginning work in this area.

The thermal potential of abnormally warm aquifers is not widely exploited at present. The Department of Energy, however, is currently funding two demonstration projects in these eastern systems. The first will use geothermal water from the Balcones fault zone to provide heating for the Torbett-Hutchings-Smith Memorial Hospital at Marlin, Tex. Warm water of about 60°C (140°F) is expected at 1.2 kilometers (3,900 feet).

A second project will use the hot brines from the thermal brine field in southern Arkansas to generate electricity. Arkansas Power and Light Company will use 99°C (210°F) brine in a binary-cycle generator to provide 100 kilowatts of electrical power.

Deep Sedimentary Basins with Normal Gradients

The geothermal energy of warm springs, shallow thermal aquifers, and radiogenic plutons can be classified as indicated resources and, to a lesser extent, as reserves. The geothermal energy associated with deep sedimentary basins cannot, however, be classified as a resource.

Many deep sedimentary basins have been delineated through petroleum exploration (Fig. 5). Except for the Appalachian, Illinois, and Michigan Basins, sediments thicker than 1.5 kilometers (5,000 feet) occur only in the interior basins associated with the Ouachita, Wichita, and Marathon structural belts of Texas and Oklahoma.

The interior basins are established on continental crust where the basement has been depressed either by gentle downwarping, as in Illinois and Michigan, or by major downwarping associated with mountain building activity, as in the Appalachian, Anadarko, Arkoma, and Ardmore basins. The thick sedimentary sequences in these basins offer targets for fluid production and --because of their great depths--relatively high temperatures. The production capabilities of many of these deep reservoirs and their temperatures are known from petroleum operations. Much of the data remain in company files, but some are available in scattered published reports.

Review of Figs. 5, 7, and 8 shows that most of the deep sedimentary basins in the interior have relatively normal heat flow and temperature gradients. Heat flow in most cases should be about 1 to at most 1.5 HFU. Temperature gradients are generally 18.2 to 29°C/km (1 to 1.6°F/100 feet), although in some cases they reach 36°C/km (2°F/100 feet).

Several of the interior basins are thought to hold fluids at a hydrostatic pressure greater than normal for a given depth. A general description of these geopressured basins is given by Wallace and others (1979). Deep wells drilled for petroleum production in geopressured regions may provide economic geothermal resources if the drilling costs can be written off to oil and gas exploration. Pumping the geothermal fluid from geopressured reservoirs would be less costly.

Undiscovered Resources

On the basis of the foregoing discussion some broad inferences can be drawn about the potential for undiscovered geothermal resources in the eastern United States.

The geothermal resource base is generally considered to be the heat in the earth's crust beneath a specific area where subsurface temperatures are higher than the local mean annual temperature (Muffler and Cataldi, 1978). By this definition, potential geothermal resources underlie all parts of the country. At the present time, however, only waters with temperatures above the average for their source area are being used for their heat content.

Most of the following discussion centers around the possible causes and locations of geothermal occurrences. In the eastern United States these seem to be limited to cases governed by elevated heat flow from radioactive plutons, insulating layers of low-conductivity sediments, deep circulation and rise of ground water, or a combination of these mechanisms. It is not likely that cooling igneous bodies are near enough to the surface to provide locally elevated heat flow.

Diment and others (1975) suggest that maximum heat flow above plutons in the eastern states is about 2.3 HFU. For comparison, Costain and others (1977, 1978, 1979) report maximum observed heat flow values of 1.9 HFU in the Atlantic Coastal Plain and 1.53 HFU above plutons in the Piedmont. The highest heat production in the basement is from large granitic bodies rich in uranium and thorium. Such granites are commonly associated with high-grade metamorphic complexes that have not undergone further metamorphism after the emplacement of the granite. When possible values of heat flow are considered, together with rock conductivities and desired temperatures (Fig. 9), it becomes apparent that thick sequences of poorly conducting sediments must overlie such radioactive granites if elevated temperatures are to develop.

Data available from published basement geologic maps, drill holes, and geophysical studies, coupled with geologic interpretation of regional trends, should yield important clues to the location of large plutons meeting this requirement. Figure 12 shows, among other features, possible locations of felsic batholithic rocks that could exist at relatively high temperatures, given sufficient sedimentary cover.

In the eastern U.S. sediments of lowest conductivity are found in the Coastal Plains. The Gulf Coastal Plain is known to have many areas of geothermal potential. The potential in the Atlantic Coastal Plain, however, is less well known. Heat flows between 1 and 2.3 HFU and conductivities between 3 and 5 CU are apparent limits for the Atlantic Coastal Plain. Sediment thicknesses are less than 1.5 kilometers (5,000 feet) except in the Delmarva Peninsula and extreme eastern North Carolina (Fig. 5). Deep holes will probably have average conductivities near 4 CU. Hence, maximum temperature gradients of about 57.5°C/km (3.2°F/100 ft) are possible.

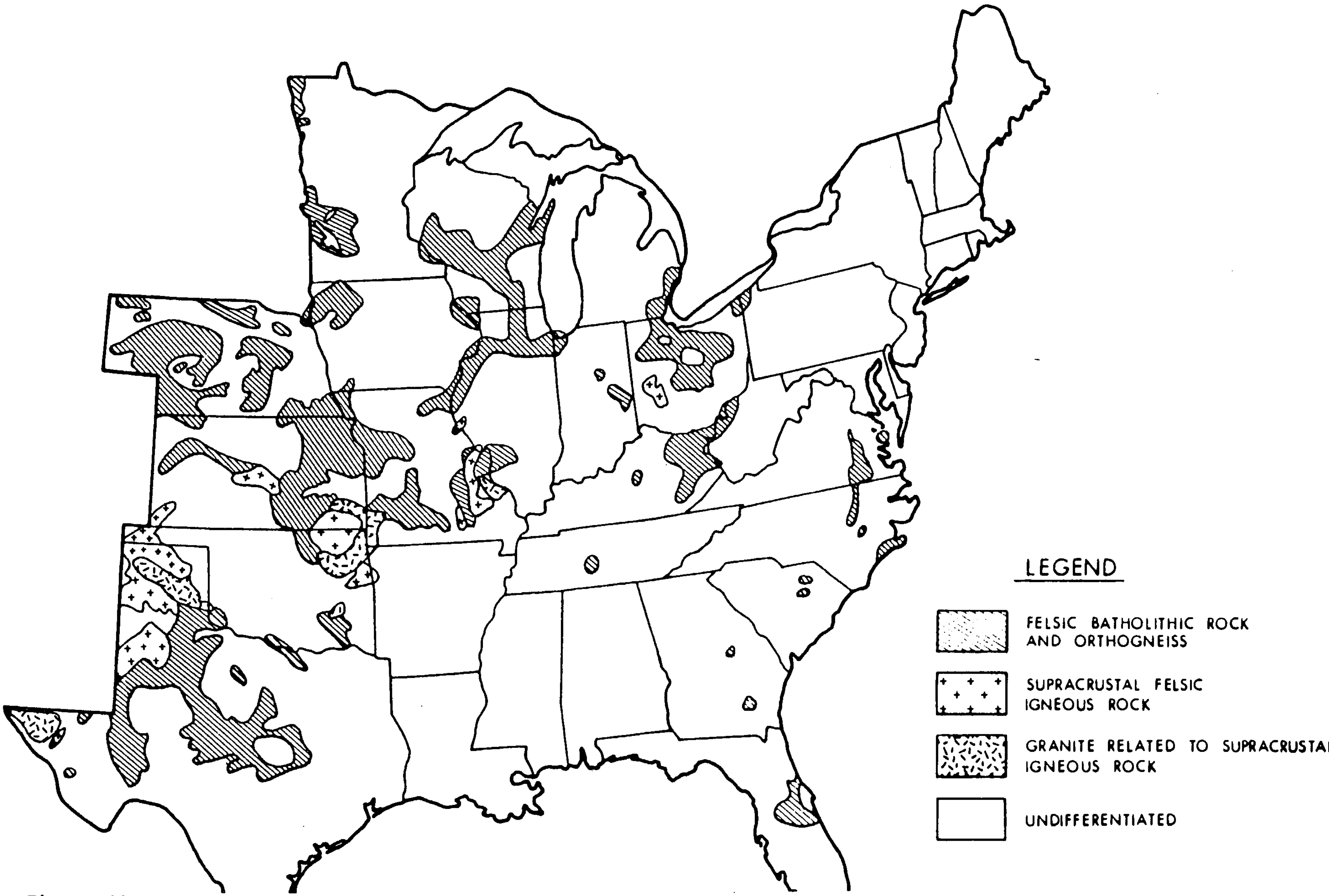


Figure 12.-- Basement geologic map of the eastern United States. Modified from Bayley and Muehlberger (1968)

Although preliminary results from the DOE Atlantic Coastal Plain drilling program suggest that temperature gradients no greater than 37.5°C/km (2.1°F/100 ft) can be expected in deep wells above most radioactive plutons in the region, the prospects are good for finding plutons with heat flows of about 2 HFU overlain by sediments with average conductivity of 4 CU. Hence, temperature gradients of 50°C/km (2.75°F/100 ft) are likely to be found with further exploration. Sediment thicknesses necessary to attain usable temperatures can be estimated from Fig. 8.

Temperature gradients away from the coast are not expected to be quite as high except in areas of very thick shale sequences, such as the Devonian shales in the Appalachian region (Fig. 13). Therefore, evaluation of conduction-dominated geothermal resources should begin where sediments are thicker than about 1.5 kilometers (5,000 feet) and temperature gradients are elevated. Figure 14 points up areas where sediments are thicker than this and where temperature gradients are greater than about 29°C/km (1.6°F/100 ft). The geology of the basement is not well enough known to predict which areas might also be underlain by radioactive plutons.

Movement of water through steeply dipping sediments or fracture zones is the other mode of heat transport in the eastern states. As discussed earlier, the warm springs of the east seem to originate from deep circulation in areas of normal continental heat flow. Since all warm springs in the east are found in similar geologic settings--steeply inclined sedimentary beds with quartzites and possibly also transverse faults present--similar environments elsewhere should be reviewed. The foremost examples are in the Folded Appalachians and in the Ouachita structural trend, where the beds are found exposed as well as extending beneath younger rocks. Several areas of the Blue Ridge and Piedmont, particularly in the southern sections, can be included here.

An extension of the Valley and Ridge style of folding underlies the Champlain River valley; this may provide another target for further investigation. Water temperatures in this geologic setting are unlikely to exceed about 60°C (140°F). Areas where these geologic conditions are possible are shown in Fig. 14. The absence of warm springs in non-mountainous areas of tightly folded rocks may imply that topographically controlled hydraulic gradients are also necessary for development of warm springs.

The major zones of faulting in the eastern United States are shown in Fig. 3, along with other structural features. Except in the Balcones and Gulf Coast sections of Texas, Arkansas, and possibly other states of the Gulf Coastal Plain, abnormally warm waters are not known to exist in fault zones of the east, although warm springs are almost invariably associated with faults in the Basin and Range province.

The Triassic basins have associated fault zones along which major vertical movements must have occurred, yet no thermal anomalies are known to be associated with these basins. Rodgers (1970) mentions that silicification is common in the faults bounding Triassic basins; perhaps faults of this age have been thoroughly sealed through alteration and cementation. Deep, waters with high temperatures and greater chemical activity may have sealed the deeper portions of fault zones over tens of millions of years, even if the upper portions are relatively open to passage of water.

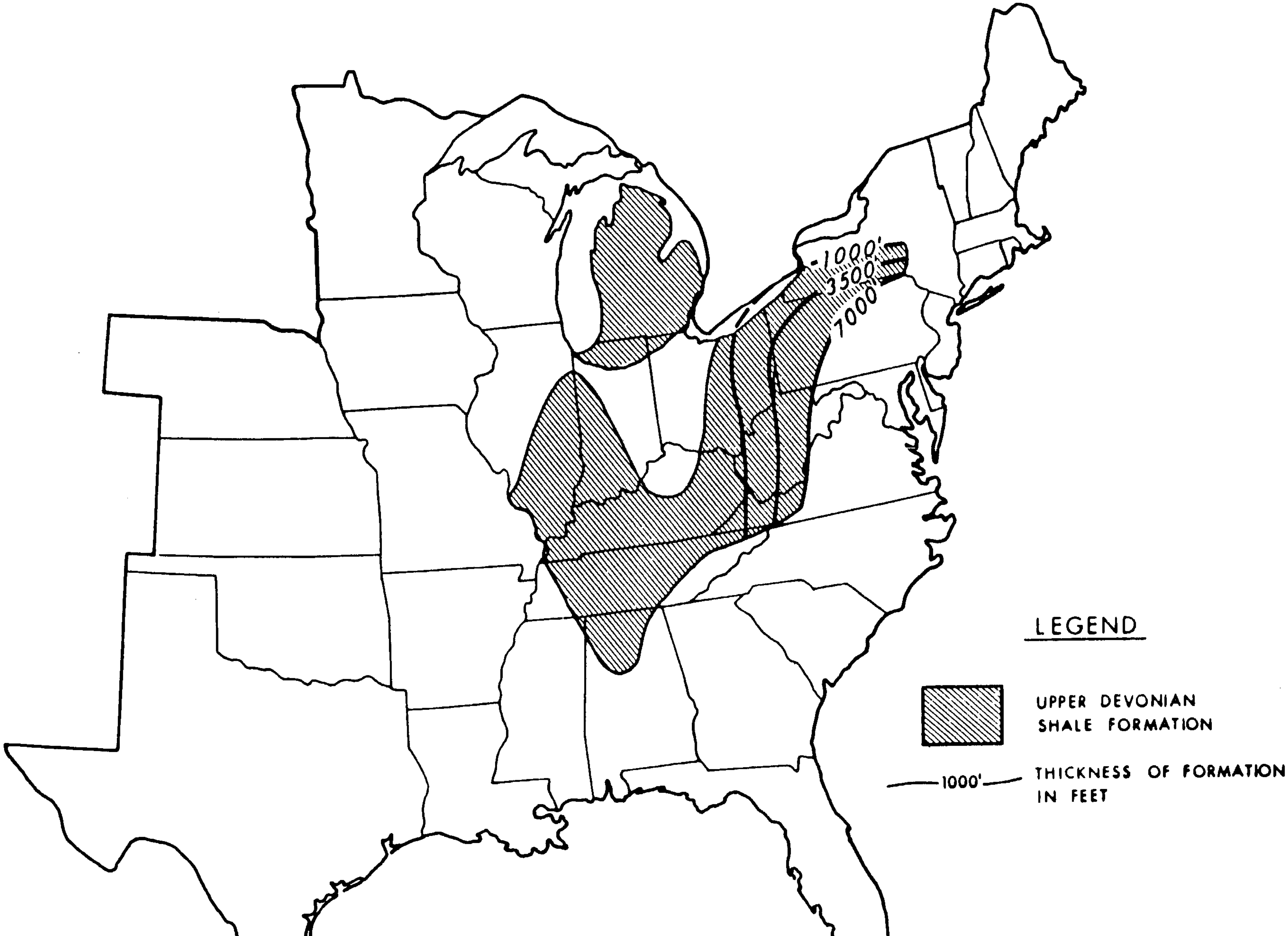


Figure 13.-- Devonian shale basin of the eastern United States by Cremean (1978).

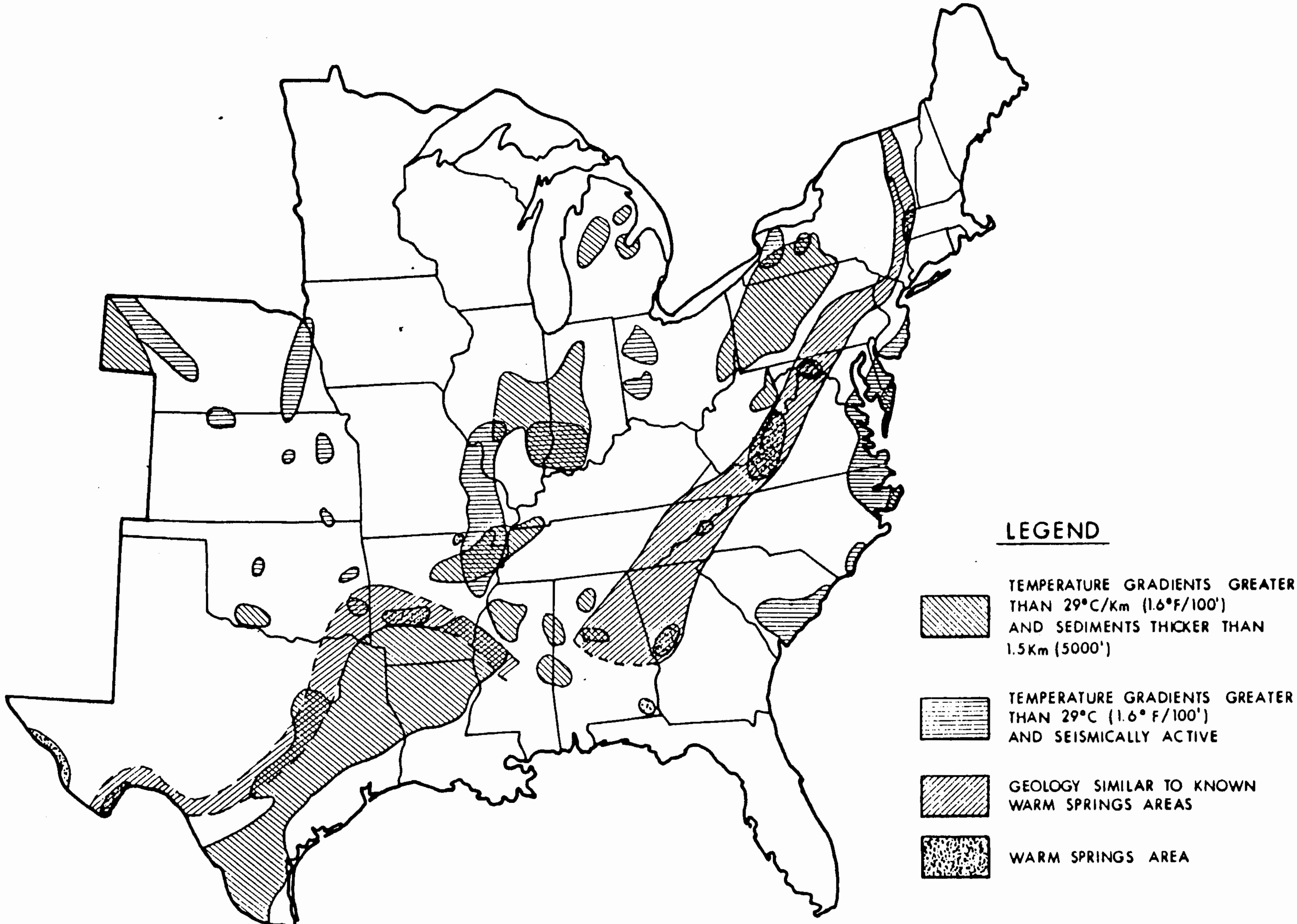


Figure 14.-- Areas of geothermal potential in the eastern United States.

The survey by Swanberg and Morgan (1978) of silica geotemperatures in ground water shows relative highs in several areas of recent seismic activity, such as New Madrid, Mo., northern New York, and South Carolina. This suggests that efforts to seek out deep fluid circulation systems should be concentrated in areas of recent seismic activity. More detailed geochemical modeling in such areas may be the most cost-effective means of geothermal reconnaissance in the east. Maps like those of Stover (1977), Hadley and Devine (1974), and Woollard (1958, 1969), portraying historic seismic activity and tectonic features, may be useful for this purpose.

Study of the temperature gradient map (Fig. 7), the major structural features map (Fig. 3), and seismic data, particularly the seismic zones suggested by Woollard (1958, 1969), points up trends that may be geothermally significant. Among these are the Chadron-Cambridge Arch-Central Kansas Uplift trend; the Nemaha Uplift-Mid-Continent Gravity High trend from Oklahoma to Nebraska and perhaps to Michigan; and the less well defined trend from New Madrid, Mo., northeastward through southern Illinois and Indiana, west central Ohio, western Pennsylvania, and New York into the St. Lawrence River Valley. Areas where temperature gradients greater than 29°C/km (1.6°F/100 feet), structural features, and seismic activity coincide are shown in Fig. 14.

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